# ATOMIC ENERGY

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*General Editor*

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# ATOMIC ENERGY

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# PREFACE

In the pages that follow an attempt is made to describe the developments in physics which first caused scientists to believe that a vast amount of energy is locked up in atoms and which eventually led to its release. The story has its beginning in the early years of the present century, and, as will be seen, success in the release of atomic energy has been achieved because of the efforts of many men, working at different times and in different places, each making a contribution to atomic physics, or, not less important, to the experimental methods of the subject. Knowledge of the atom has been obtained gradually and as a result of painstaking investigations.

In order to obtain an understanding of modern views of atomic structure and of the release of atomic energy, it is desirable to review the course of scientific discovery in these fields. The story of atomic energy commences with the discovery of radioactivity at the end of last century, when experiment had just revealed the electrical nature of matter. This discovery that all atoms contained electrons led to theories of atomic structure, but a considerable period elapsed before the picture of the atom contained sufficient detail to explain the facts of radioactivity.

The account given in subsequent pages describes the growth of knowledge of atomic structure and attempts to provide a background of knowledge to enable the reader to obtain a clear picture of the circumstances in which energy is obtained from atoms.

The amount of detailed explanation that a book can provide depends upon the assumptions the author makes concerning the knowledge of the reader. This book is intended primarily for those with some scientific knowledge; even if this knowledge is not extensive, or indeed very modern, it should suffice to make the book comprehensible. No detailed knowledge of atomic structure is assumed; the necessary ideas are put forward in the first four chapters. Chapters 5 to 8 give some account of modern experimental techniques in atomic physics and of important discoveries to which they have led. Subsequent chapters describe the details of processes which have been found to yield atomic energy and the arrangements which are used to release it on a considerable scale. The last chapter of the book is concerned with the future of atomic energy and in it are considered some of the consequences which may follow from the success already achieved.

The writing of a book on atomic energy is made difficult because some information which is of interest and importance must be kept secret. In consequence, there are certain matters on which I have knowledge that I am not permitted to reveal, and there are many more on which I have no information except that contained in *Atomic Energy for Military Purposes* by H. D. Smyth.* In some few places it is not possible to do more than retell what Smyth has already told, but normally, with the help of his report and the information published prior to the war, a reasonably detailed picture of the means for releasing atomic energy can be presented.

I wish to place on record my gratitude for the help that has been given me by two of my colleagues. Prof. P. B. Moon read my manuscript in its early stages, and certain parts of the book have been influenced by my discussions with him. Later on Mr. D. F. Bracher read the manuscript with great care and has been instrumental in having removed numbers of errors and obscurities. He has also taken much trouble and has rendered most valued assistance in reading and correcting the proofs.

I also wish to express my thanks to Dr. A. C. B. Lovell, for the kindness and helpfulness he has shown me during the preparation of this book.

Finally I am indebted to the Cambridge University Press for permission to reproduce Figs. 5, 6, 7, 8, 9, 10, 13 and 21, to the American Institute of Physics, Inc., for permission to reproduce Fig. 24, to Mr. Ejnar Munksgaard of Copenhagen for permission to reproduce Figs. 25 and 26, to the Directorate of Atomic Energy of the Ministry of Supply for the loan of photographs from which Figs. 33, 34, and 35 are reproduced and to Major Robt. J. Coakley of the War Department, Washington, D.C., for the supply of photographs which are reproduced as Figs. 39 and 42.

* Princeton University Press, Princeton, N.J., U.S.A. The text of this report is published by H.M. Stationery Office: "Atomic Energy" (1945), S.O. Code No. 59-87.

## CHAPTER I

# INTRODUCTION

In the middle ages the transmutation of metals was widely accepted as a possibility. Admittedly, the experimental support for this view was not entirely satisfactory, and there were insuperable difficulties in achieving the type of transmutation which was supremely desired, that of changing a base metal into gold. But considerations of this sort were not sufficient to deter many a philosopher from wasting years of his life in attempts to achieve what we now know he had hopelessly insufficient means to effect. Belief in the philosopher's stone, though long-lived, could not be accepted in the face of growing knowledge of chemistry.

As investigation proceeded, the laws of chemistry began to take shape. It became clear that when a chemical reaction occurred the masses of the reacting substances were just equal to the masses of all the products. Furthermore, energy relations were discovered, and these showed that the heat developed in a given chemical change was a constant, which did not depend on the way in which the change was carried out. From experiments investigating such matters arose two very important chemical laws, the law of the conservation of mass and the law of the conservation of energy.

Further experiments served to verify that certain chemical substances could neither be broken into simpler ones nor synthesized from others already known. Eventually, between eighty and ninety of these substances were recognized and were listed as the table of elements; from consideration of the properties and combining masses of these elements, the periodic atomic table was drawn up. The atomic theory of matter was accepted, and formed the basis of much of chemical theory. At that time there was no possibility of detecting the presence of a single atom, and it was assumed, therefore, that all atoms of a given element were identical. The evidence in support of this view was overwhelming, for the only cases in which different samples of an element were found to differ were just those in which an unsuspected impurity, perhaps a new undiscovered element, was present in one or other of the samples.

It will be appreciated that the fundamental conception of an element involved the assumption that one element could not be converted into another. Not only had the quest for the philosopher's stone been abandoned, but the ideas commonly held towards the end of the nineteenth century were based on the assumption that transmutation of any kind was impossible.

That was the period in which some physicists believed that physics as a science was almost complete and that there were only one or two odd points to clear up. There were of course many things to measure with greater and greater accuracy, but to these people physics was about to become a dead science. Not all the beliefs of those days were right! By good fortune this was not the direction in which physics developed.

In the last decade of the nineteenth century radioactivity was detected. This discovery contributed to no small extent to the overthrow of the simple ideas concerning atoms and the laws of conservation of mass and energy. For much of chemistry these conceptions are as useful to-day as when they were first proposed, but for physics, especially for atomic physics, great advances have been made by refusing to accept the exact validity of these ideas, despite their usefulness in the development of chemistry.

## CHAPTER II

# FUNDAMENTAL IDEAS CONCERNING ELECTRONS AND ATOMIC STRUCTURE

(1) *Electrons.*

Before we discuss the discoveries that were made at the close of last century, it is desirable to describe modern ideas of the structure of atoms and of the arrangement of the elements in the atomic table.

Although knowledge of electrical theory was well advanced during the course of the nineteenth century, the last decade was in its second half before the existence of the negative electron was established. Not only did the newly discovered electron provide an entity which was assumed to be a constituent of all atoms, but it also provided a natural unit of electric charge ; as was determined later this particle carries the very small charge of $1.6 \times 10^{-19}$ coulombs. Any charge, if negative, arises from the presence of so many additional electrons, while a positive charge, which we find can be exactly neutralized by a sufficient number of electrons, is also expressible in terms of the same unit. This unit of charge is commonly used throughout this book.

The discovery of the electron was followed by investigations of its properties, and once it was recognized as a charged body experiments were made on electrons of given speed in order to determine their mass, their charge and their velocity.

It was known that in a uniform magnetic field a charged particle travels in a circle, the radius of which depends on the mass, the velocity and the magnitude of the charge carried by the particle, as well as on the strength of the magnetic field in which it moves. Again, from their very nature, charged particles are influenced by electric fields ; if then electrons move in the electric field established between parallel conducting plates which are connected to opposite terminals of a battery, the electrons will describe a parabola, the dimensions of which depend upon the mass, the velocity and the charge of the electron as well as on the strength of the electric field. Investigation of the motion of charged particles in electric and magnetic fields, and in combinations of these fields, has shown that it is possible to determine the velocity of the particle and the ratio of its charge to its mass ; from such experiments it is not possible to determine independently either the mass or the charge.

Although it was desirable to determine both the charge and mass of the electron, it was realized that even the ratio of charge to mass was likely to afford useful information concerning its nature. Faraday's investigation of

the laws of electrolysis had shown that a certain electric charge, which we now believe to be $9.65 \times 10^4$ coulombs, was necessary to liberate about 1.008 grams of hydrogen or greater weights of other substances. On the views which had long been accepted, electrolysis of water involves the motion of positively charged hydrogen atoms within the liquid ; as we have just seen, these atoms carry a charge of about $10^5$ coulombs per gram. This figure has to be compared with the results of measurements of the ratio of charge to mass of the electron, measurements which showed that the electron was quite different in nature from any known atom ; for an electron, the ratio of charge to mass is $1.76 \times 10^8$ coulombs per gram. It was assumed that the positively charged hydrogen atoms which took part in electrolysis were positively charged because they lacked one electron ; in other words the positive charge on the hydrogen atom was the same in magnitude as the negative electronic charge. On this assumption, the mass of the electron was less than one thousandth of that of the hydrogen atom.

(2) *Energy of electrons* : *The electron volt.*

One aspect of the motion of an electron in an electric field should be examined before attention is directed to the theories of atomic structure which arose from the discovery of the electron. When an electron moves from a point of low potential to one of higher potential, it is assisted by the force imposed by the electric field, and in consequence it gains kinetic energy ; the gain in kinetic energy is proportional to the potential difference through which the electron moves. It is useful to measure the kinetic energy of an electron in terms of the potential difference through which it must fall from rest in order to gain this energy. If e is the electronic charge, an electron starting from rest at a point at zero potential will have kinetic energy Ve when it reaches, by any path at all, a point at potential V. As the kinetic energy is $\frac{1}{2}mv^2$, where m is the mass of the electron, we have the equality

$$Ve = \tfrac{1}{2}mv^2,$$

from which, if we wish, we may determine v, the velocity of the electron in terms of V and e/m. This relation, however, is most useful as a definition of a unit of energy. As the electron carries a charge of $1.6 \times 10^{-19}$ coulombs, it possesses a kinetic energy of $1.6 \times 10^{-19}$ joules after falling from rest through a potential of 1 volt. We say that this electron has an energy of " 1 electron volt " or 1 eV. Fig. 1 shows that the electron gains an energy eV in going from potential zero to potential V ; the energy gained does not depend upon the route between the starting point at zero potential and the finishing point at potential V.

The use of the electron volt can readily be extended to measure the energy of any particle, charged or uncharged. If we talk about a gas atom having

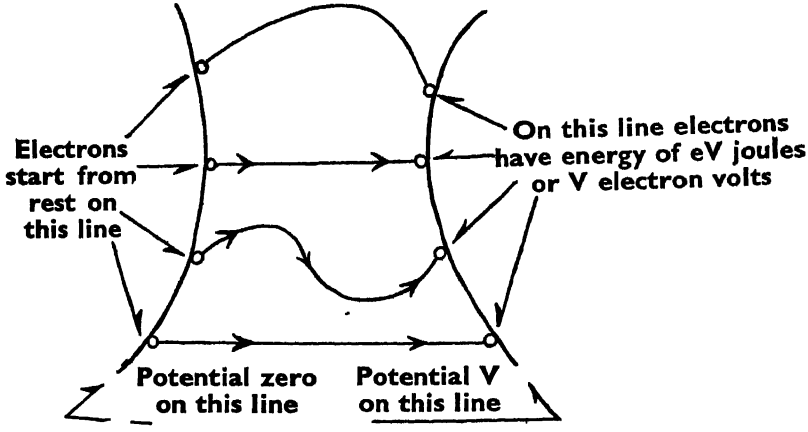


**Fig. 1**

an energy of 10 eV, we mean that its energy is the same as that possessed by an electron which has fallen from rest through a potential difference of 10 volts; as the unit is one of energy, it can be used in speaking of any kind of body, although in practice it is useful to employ it only for measuring the energies of atoms and molecules, sub-atomic particles and radiations.

A unit of energy of $1.6 \times 10^{-19}$ joules appears to be an inconveniently small one in which to measure energies, and for laboratory measurements of heat energy, for example, where we are considering the total energy shared among perhaps $10^{20}$ atoms, this is indeed the case. On the other hand, the unit is a convenient one in which to discuss the average energy possessed by each of the atoms in the amount of matter being considered, for in atomic processes, where we are concerned with the interaction between individual atoms, it is essential to consider their energies. We illustrate the idea by considering the kinetic energy of a single atom of a monatomic gas at a temperature of 0°C. The average value of this energy is known to be $5.6 \times 10^{-21}$ joules, or 0.035 eV, an energy which is very small compared with what is readily communicated to electrons. A more striking example of the use of the electron volt is obtained by using it to express the mean kinetic energy of monatomic gas atoms at the very high temperature of $10^6$ °C. At this temperature, which is not normally attainable on the earth, the mean kinetic energy of a gas atom is $2 \times 10^{-17}$ joules, or about 130 eV. Temperature is a very powerful influence in breaking apart chemical compounds, but even the very highest temperatures normally available to us cannot achieve results

which can readily be obtained by using electrons or other charged particles which have been accelerated by falling through a few hundreds of volts. There is no simpler way of emphasizing this than by expressing in electron volts the mean kinetic energy of the atoms of a heated substance.

(3) *Electrons and atomic structure.*

Soon after the discovery of the electron, it was realized that this particle was probably a constituent of all atoms, for electrons were found to be present in any gas discharge tube through which an electric current was passed. These electrons had evidently been detached from gas atoms within the tube, for it was also possible to show the presence there of positively charged gas atoms. This process by which gas atoms are divided into pairs of oppositely charged particles is known as ionization; some of the gas atoms are ionized or transformed into ion pairs, each consisting, initially, of a positively charged gas atom—a positive ion—and an electron. In some circumstances the electron attaches itself to an electrically neutral gas atom or molecule to form a negative ion. Ionization of gases occurs as a result of impacts between gas atoms or gas molecules and electrons having energies of some 10—30 eV; it can also be brought about by atoms of much higher energies as well as by other processes.

It will be realized that as gas atoms are normally without electric charge, they must contain a source of positive charge which is exactly neutralized by the electrons within the atom. The early experiments did not afford any experimental information concerning the nature of the portion of the atom carrying this positive charge. For some time, therefore, it was assumed that the positive charge consisted of a sphere of positive electricity within which the electrons were embedded. It was also believed that different elements differed chemically because of differences in the numbers of electrons within their atoms, but at that time and for some considerable period afterwards there was no accurate means of determining the number of electrons in an atom of a given chemical element.

Theories of atomic structure were put on an experimental basis in 1911, when Rutherford carried out investigations with the swift charged helium atoms emitted by some radioactive substances. When these $\alpha$ particles, as they are called, were allowed to fall on a thin sheet of gold, it was found that a few of the particles were turned back on their paths. From this observation and further experiment it was concluded that atoms of gold contained small and massive centres carrying very strong electric charges; furthermore, it was shown that the charged centre within the aluminium atom carried a smaller charge than in the case of gold.

As a result of these experiments a new atomic theory—the nuclear theory —was proposed. It was believed that the atom consisted of a central core or nucleus which contained almost the whole mass of the atom and carried a positive charge equal in magnitude to that carried by the electrons which completed its structure. These electrons were believed to rotate about the nucleus in various orbits; some orbits were close to the nucleus, others were much further away. All these orbits, though small in themselves, were enormous compared with the size of an electron or of a nucleus, so that the region traversed by the electrons was very large compared with the size of the particles of which the atom was composed. In many respects the atom model was just a miniature solar system in which the forces were electrical and not gravitational and in which the nucleus took the place of the sun and the electrons that of the planets. Fig. 2 illustrates the structure at one time assumed for an atom with three electrons rotating about a nucleus carrying three positive charges.

This nuclear theory of the atom was satisfactory as far as it went, but there was one serious weakness in it, for although it was realized that the properties of an atom would be related to the number of electrons rotating around its nucleus, this number was not known, and at that time there was no accurate means of measuring it, either directly or by determining the value of the positive nuclear charge.

The nucleus is represented by the small dot within the orbits. If the nucleus were drawn to scale it would be invisible.

$10^{-8}$ cm.

**Fig. 2**

(4) *Atomic number.*

As has been mentioned previously, the chemists had arranged the elements in the order of their atomic weights and as a result of studies of the properties of the known elements they had been led to the atomic table.* In this table the elements were arranged primarily so as to exhibit their chemical properties, but in all but one or two isolated cases the order of arrangement was also that of their atomic weights. As the early theories of atomic structure were developed, attempts were made to relate atomic properties to the magnitude of the positive charge on the nucleus of the atom exhibiting the properties. In this direction a great advance was made by H. G. J. Moseley, who, in 1914, after making a study of X ray phenomena, proposed that the position of an

* On pages 191, 192 and 193 will be found a list of elements and the periodic table.

element in the periodic table was related to the number of positive charges on its nucleus. In particular he believed that of two neighbouring elements in the periodic table, the heavier one had one more charge on its nucleus than had the lighter one. Moseley assumed that aluminium, the lightest element he investigated, had thirteen positive charges on its nucleus, and from a study of the atomic table he was able to determine the nuclear charges of all the elements in the atomic table. The number of charges on a nucleus is now known as the atomic number and is often represented by Z; Moseley's work showed a way of determining the atomic number of every element. But although Moseley determined correctly the charge on the nucleus and so the atomic numbers of the elements, his approach was indirect, and it was not until some years later that Chadwick verified that the nuclear charge was indeed equal to the atomic number chosen by Moseley.

This idea of nuclear charge and atomic number is now realized to be most important. The nuclear charge determines the number of electrons in an atom and the number of electrons there determines the chemical nature of the atom. For this reason the atomic number of a substance is just a numerical name. If we give either the name of an element or its atomic number there is equal certainty as to the chemical properties of the substance of which we are talking. On turning to the table of elements, we see that the atomic number of neon is 10. The neon atom has a nucleus with 10 positive charges and around this rotate ten electrons. Now we shall see later that every neon atom is not the same as every other neon atom, but every neon atom has ten nuclear charges and every atom with an atomic number of 10 is a neon atom. It is apparent from what has been said that the atomic number is not directly related to the atomic weight of an element. In the periodic table the elements are arranged in order of ascending atomic number; in this order, which is not always the order of ascending atomic weights,* the elements show the repetition of chemical properties that we associate with that table.

(5) *Atomic weight and mass number.*

Some discussion must now be given of the atomic weights of the elements. It was proposed by Prout, in 1815, when the quantitative study of chemistry was in its infancy, that all atoms were made from hydrogen atoms, and that all atomic weights should therefore be multiples of that of hydrogen. Later accurate measurements of atomic weights showed this view to be untenable; in many cases there was support for Prout's hypothesis, but the instances in which it did not apply were soon verified with sufficient accuracy to discredit the hypothesis. Much more elaborate and difficult experiments were needed before the essential truth of Prout's hypothesis was patent. These

* Compare the pairs of elements Co and Ni, Te and I, and A and K.

experiments were commenced about 1913 when J. J. Thomson passed a beam of fast positive ions of neon through electric and magnetic fields; his observations could be explained only by assuming that the gas neon with an atomic weight of 20.2 was not a single substance. It was apparent that it consisted of one type of neon with an atomic mass of very nearly 20 and a small amount of another type of neon with an atomic mass of very nearly 22. The atomic masses of the two types of neon were measured indirectly, but the measurements were sufficiently accurate to show that the experimental values were very close to the integers 20 and 22. It was clear that there were two kinds of neon, just as there were later found to be two kinds of chlorine. Of course, both neons had the same atomic number of 10 just as both chlorines had the same atomic number, in that case 17; furthermore, both neons had the same chemical properties and so also with both chlorines. For this reason the two neons were spoken of as the neon isotopes, and more generally when we mention the isotopes of any element we mean all of the substances, whatever their atomic masses, that have the atomic number and the place in the periodic table appropriate to the element under discussion.* As a result of the discovery of the existence of isotopes amongst light elements—radioactive isotopes had been known for some time previously—and the knowledge that the atomic masses of the individual isotopes were very close to being integers, Prout's hypothesis was revived and it was assumed that the atomic mass of every isotope was an exact integer. Although this is very nearly correct, it is only an approximation, as was found when more accurate atomic mass measurements were made. Nevertheless this integer, to which the atomic mass of any single isotope is found to approximate, is of sufficient importance to be given a name and a symbol; it is called the mass number and is often represented by A. In these new terms we would say that J. J. Thomson discovered that neon ($Z = 10$) consisted of two isotopes of mass numbers 20 and 22. Similarly chlorine ($Z = 17$) consists of two isotopes of mass numbers 35 and 37. We could go further and state the exact value of the atomic mass of each of the isotopes specified above, but for the present to do this would introduce unnecessary complications.

Further information concerning the subject matter of this chapter will be found in the following: "Ions, Electrons and Ionizing Radiations", J. A. Crowther, (Arnold); "Electrons, Protons, Photons, Neutrons and Cosmic Rays", Millikan, (Chicago).

* Isotope: literally "the same place."

## CHAPTER III

# RADIOACTIVITY

(1) *Nature of radiations and resulting nuclear changes.*

We now consider the discovery mentioned in the concluding paragraph of Chapter 1. In February 1896, Henri Becquerel discovered radioactivity when he performed an experiment similar to one which was carried out by Röntgen a few months earlier and which resulted in the discovery of X rays. Becquerel found that uranium salts gave out a radiation which was able to pass through a thin silver sheet and fog a photographic plate. The details of the phenomenon were not at that time understood, but Becquerel's discovery was followed by great experimental activity in which Rutherford and the Curies, amongst others, took a prominent part. As a result, by 1903, much was known about the heavy elements which emitted radiations spontaneously; the novelty of these new phenomena, called radioactivity, was apparent.

It was soon realized that there were a large number of radioactive substances. Each of these was found to emit radiations spontaneously. Some emitted radiations which Rutherford called $\alpha$ rays. These rays, now usually called $\alpha$ particles, were found to be helium atoms carrying two positive charges and moving at great speed; they were able to produce intense ionization along their paths, but as their penetrating power was small, their effects in air at atmospheric pressure were confined to distances extending only a few centimetres from their source. A radioactive element emitting $\alpha$ particles was found to transform itself into a substance which was chemically different from that from which the $\alpha$ particles came. The new substance had an atomic weight smaller than the parent, and in terms of modern ideas its mass number was 4 units less than that of the parent atom. If we take as an example the substance radium, with a mass number of 226, we find that it emits $\alpha$ particles, which are able to traverse 3.4 cm. of "standard air," i.e., air at 15°C. and 760 mm. pressure, and yields radon, a rare gas which is itself radioactive and which has a mass number of 222. Now radium is chemically similar to barium, and radon is similar to the rare gas xenon, and in the atomic table radium is placed in the position corresponding to an atomic number 88 while radon occupies the place of an element of atomic number 86. This example—and many similar ones could be named—shows that when an $\alpha$ particle is emitted, the new element has an atomic number two less and a mass number four less than the substance from which it was formed.

It is evident that the reductions of mass number and nuclear charge are a direct consequence of the emission of the α particle, which carries off two of the charges and four of the mass units originally part of the nucleus.

Not all radioactive substances emit α particles. Many emit β rays, particles which have negative charges, high speeds of emission and very high ratios of charge to mass. Careful measurements have shown that these particles are simply high speed electrons. They, too, come from the nucleus of the parent atom, but they carry so little mass that their departure involves no change in mass number. On the other hand the removal of negative charge involves an increase in the positive charge of the nucleus, and as the electron takes off one negative charge the atomic number of the nucleus increases by unity. As an example of this process we may take the radioactive substance radium D.* Chemically this substance has all the properties of lead, but it is distinguished from lead by its radioactive emission of β particles. Now lead and radium D have atomic number 82, and radium D has mass number 210; upon the emission of a β particle radium D is transformed to radium E, still with mass number 210, and with atomic number 83. Radium E, which is an isotope of bismuth, emits β particles and on doing so becomes radium F or polonium, a substance with atomic number 84 and mass number 210. Polonium emits α particles and gives rise to a substance of atomic number 82 and of mass number 206. The atomic number of this substance shows it to be lead, and in fact it is not radioactive and it is one of the constituents of ordinary lead. From this example we see that when there is successive emission of an α particle and two β particles, in any order whatever, the initial substance is chemically identical with the final one, but the two substances differ by four in mass number. These two kinds of lead are of course isotopes; the process has been discussed in detail in order to show that normal radioactive transformations are likely to produce numerous isotopes.

(2) *Radioactive isotopes.*

When one is told that the natural heavy radioactive substances comprise nearly forty different kinds of atom, all of which have such atomic numbers that they occupy ten places in the periodic table,† one can readily understand why the existence of radioactive isotopes caused great confusion when early attempts were made to explain radioactive processes and to make chemical separations of the products of a substance such as radium. An understanding of these radioactive transformation processes caused something of a shock to

* At the end of the book is a diagram showing the radioactive transformations to which the heavy nuclei are subject.

† Compare the diagram of radioactive elements on page 193.

those who accepted the ideas usually held about chemical elements. Radioactive processes were such that one element was being transformed steadily into another; the evidence was firmly established, and although radioactive substances were regarded as exceptional, it was impossible to maintain any longer that no element could be converted into another. Then, there was the surprising existence of so many radioactive isotopes. Were the radioactive elements again an exception or did other elements in the periodic table possess isotopes on the scale exhibited by the heavy radioactive substances? This question was one to which an answer could not be provided in the early years of the present century. Nevertheless, when later on it was shown that many light elements possessed two or more isotopes, there were some who were dubious about accepting the experimental evidence, even though this evidence did no more than show that in this respect the radioactive substances were not exceptional and occurred in a variety of isotopic forms just as did non-radioactive substances.

It is probable that there was then little realization of the similarity between radioactive and other elements. The existence of $\beta$ radioactivity amongst light elements, as was discovered thirty years later, was not predicted from analogy with the heavy radioactive elements. In other words, radioactivity continued to be regarded as an exceptional phenomenon, exhibited almost exclusively by the very heavy atoms, and the properties of radioactive atoms were not thought of as being those of atoms in general. There was one good reason for this point of view and that was the spontaneity of the radioactive processes. If we consider 1 gram of radium, we find that a constant number of $\alpha$ particles is emitted every second, and a constant amount of radium is transformed into radon. The rate of emission of $\alpha$ particles is unaltered by any chemical or physical process to which the radium is subjected, and the transformation of radium into radon is a process on which man's experiments have no perceptible effect. It was clear that the radioactive process involved mechanisms which were of an entirely different nature from those experienced in chemical reactions.

(3) *Radioactive transformations.*

It is not quite correct to say that the radium transforms itself at a constant rate. In fact the number of atoms being transformed in one second is proportional to the number N of radium atoms present, and is generally written $\lambda N$, where $\lambda$ is a constant called the transformation constant of radium. It can be derived from this relation that the amount of radium decreases exponentially with time, that is if there are $N_0$ radium atoms present at time zero, the number N at any subsequent time t is given by $N = N_0 e^{-\lambda t}$. By making observations of the rate of emission of $\alpha$ particles

from radium, we can determine the way in which it is reduced in amount with time, and consequently we are able to determine $\lambda$. Usually, we state the disintegration rate of a radioactive substance in terms of its half life, that is in terms of the time taken for a given sample of a substance to "decay" to half its original strength. There is a characteristic half life for every radioactive substance; thorium has a half life of $1.65 \times 10^{10}$ years, radium a half life of 1600 years and radon a half life of 3.825 days; some substances have half lives of a small fraction of a second. Although the half life of radium is short compared with that of thorium or of uranium, it decays sufficiently slowly to involve quite a small diminution in its activity during the period of a man's life.

(4) *Energy liberated by radioactive substances.*

Observations made as long ago as 1903 showed that radium maintained itself at a perceptibly higher temperature than that of its surroundings. Measurement showed that the rate of evolution of heat was such that 1 gram of radium and its products evolve heat at the rate of more than 100 calories an hour. This is a very small amount of heat energy and is to be compared with nearly 8000 calories produced when 1 gram of carbon is burned to carbon dioxide. But in a year, in which the quantity of radium suffers a negligible diminution, the total amount of heat evolved is more than 800 000 calories, a quantity which is one hundred times that released when the same mass of carbon is burned. By the time that the radium has all decayed, and it will be a long time before this has occurred, the radium and its immediate products will produce about $1.6 \times 10^9$ calories or $2 \times 10^5$ times as much energy as is yielded by burning the same weight of carbon. Regarding the radium as a source of heat, it has a calorific power of nearly one quarter of a million times that of carbon. Here is a source of energy that far transcends any ordinary fuel. Radium is not regarded as being suitable for use as a fuel; it is most expensive, it is available in very small quantities, it evolves its energy at a very slow rate and in addition it produces $\gamma$ rays, radiations which though useful in hospital treatment of cancer can have serious or even fatal consequences to anyone who is exposed to considerable doses of them.* Despite these disadvantages which are attached to the use of radium as a fuel, this knowledge of the properties of radium made it clear that there were other sources of energy besides the fuels with which we are so familiar; the yield of heat energy from a radioactive substance is of an entirely different order of magnitude from the yield from any known fuel, or indeed from any chemical process either known or imagined. The question that must occur to anyone who considers the matter is that of determining the origin of the

* Compare Chapter 12, p. 130

energy liberated by radioactive substances. Little more was clear than that the process was not an ordinary chemical one, and almost the only possible answer was that the energy came from the radioactivity of the substances producing it; and this was no answer at all.

(5) *Emission of* $\gamma$ *rays from radioactive substances.*

As was stated above, radium emits $\gamma$ rays. These radiations are electromagnetic in nature, and are similar to X radiation; indeed, means are now available by which very high voltage X ray tubes can be made to generate radiations which are identical with the $\gamma$ rays emitted by the nuclei of radioactive atoms. $\gamma$ rays were not discussed in connection with radioactive transformations because the emission of $\gamma$ rays is a secondary phenomenon. The emission of a $\gamma$ ray causes no change in atomic number or in mass number, and so causes no atomic transformation; it simply serves to remove energy from an atomic nucleus which for one reason or another has more than its normal amount. The emission of $\gamma$ rays is important in relation to theories of nuclear structure, just as the emission of visible spectral radiations is important to the theories of the structure of the extra-nuclear portions of the atom.

$\gamma$ rays have many of the properties of other electromagnetic radiations such as light or wireless waves; their frequency may be determined from measurement of their wavelength, although in practice this experiment is feasible only for rather low frequency $\gamma$ rays. From the point of view of nuclear physics, it is found to be most useful to imagine that $\gamma$ rays are particles carrying energy. A $\gamma$ ray makes itself apparent only when it interacts with matter, in which circumstances all or part of its energy is transferred to atoms or more usually to electrons. When a $\gamma$ ray gives all its energy to an electron, a determination of the energy of the $\gamma$ ray may be made from a measurement of the speed or energy of the electron.

For completeness it should be mentioned that the frequency of a $\gamma$ ray is proportional to its energy E, that is to the maximum energy the $\gamma$ ray can transfer to a single atom or electron. If $\nu$ is the frequency of the $\gamma$ ray we have the relation

$$E = h\nu;$$

here h is a constant called Planck's constant; its magnitude is $6.55 \times 10^{-34}$ joule-sec. When a nucleus emits a $\gamma$ ray of a given frequency, the energy withdrawn from it is given by the equation above; occasions will occur on which this same energy is transferred by the $\gamma$ ray to an electron. In discussion of phenomena involving $\gamma$ rays, it is unusual to mention their

frequency; in general we talk of their energy which we usually express in electron volts.

Further information concerning the subject matter of this chapter will be found in the following books: "Radioactivity and Radioactive Substances", Chadwick, (Pitman); "Radiations from Radioactive Substances", Rutherford, Chadwick and Ellis, (Cambridge University Press); "Radioactivity", Hevesy and Paneth, (Oxford University Press).

## CHAPTER IV

# MASS AND ENERGY

(1) *Increase of mass with energy.*

The early days of the present century were remarkable in that accepted beliefs were being questioned and new and unlikely sounding alternatives were being proposed. In the period under review there appeared the Quantum Theory of Planck and the Theory of Relativity of Einstein. It is with one aspect of the latter that we are concerned, and by good fortune our discussion of it is in no way difficult.

The special theory of relativity is based on two postulates. These are that there is no way of determining whether one is or is not at absolute rest and that the velocity of light is the same to all observers, even in the case in which two observers are moving relative to one another. Of course this second postulate is not what is expected by people who compare the measurement of the velocity of light with the results to be obtained from measuring the velocity of slowly moving terrestrial bodies; it is not therefore surprising that the theory of relativity makes deductions which are as unexpected as the postulates.

The particular relation in which we are interested is one which shows that there is an increase in the mass of any body when there is an increase in its kinetic energy. If we increase the kinetic energy of a slow electron, we first cause a large increase in its speed and a small increase in its mass; a stage can be reached when the speed of the electron is close to that of light, and then a further increase of kinetic energy results in a very small increase of speed and in a further increase of mass. Such changes of mass and speed with kinetic energy are illustrated for the case of an electron in Fig. 3. In this case, and indeed in all cases, the increase in kinetic energy can be shown to be equal to the increase of mass multiplied by the square of the velocity of light, or writing it algebraically

$$\epsilon = \mu c^2;$$

here $\epsilon$ is the increase in kinetic energy, $\mu$ is the increase in mass and c is the velocity of light in vacuum. More generally the total energy of the electron, E, is written as $mc^2$, where m is the mass of the electron at the speed being considered. The relation is assumed to be correct at zero speed when the electronic mass is $m_0$; the electron must then possess energy $m_0c^2$, called its rest energy. When the electron moves, its energy is greater than its rest

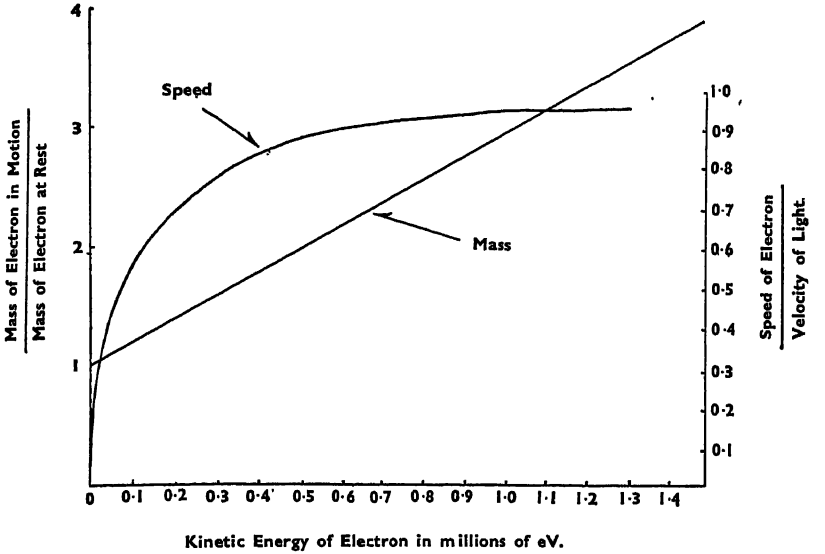


**Fig.3.** Variation of mass and speed of an electron with kinetic energy.

energy by the amount of its kinetic energy, $(m—m_0)c^2$. Einstein's theory shows that a particle of rest mass $m_0$ has, at a velocity v, the mass

$$\frac{m_0}{\sqrt{1 - v^2/c^2}};$$

thus the kinetic energy of an electron moving with a velocity v is

$$m_0c^2\left(\frac{1}{\sqrt{1 - v^2/c^2}} - 1\right)$$

At low velocities this expression is almost exactly equal to $\frac{1}{2}m_0v^2$ and so is in accord with the Newtonian laws of dynamics which apply to slowly moving bodies. The points to be stressed are that an increase of kinetic energy of an electron, or in fact of any other particle or material body, involves an increase of mass and that the increase in energy is just equal to the increase of mass multiplied by the square of the velocity of light.

Now c, the velocity of light in vacuum, is $3 \times 10^8$ metres per sec., and so an increase of mass of 1 gram corresponds to an energy of $9 \times 10^{13}$ joules.* If

* If mass is measured in kg. and velocity in metres per sec., the energy is measured in joules.

we consider the kinetic energy of a mass of 1000 kg. moving at the speed of a jet plane, or say 250 metres per sec., we find that it amounts to about $3 \times 10^7$ joules. At this speed, masses increase by about one part in three million million, and our mass of 1 metric ton is increased by only $\frac{1}{3}$ microgram.

While this is an interesting consequence of the theory of relativity, it is not very easy to verify experimentally if ordinary particles are used. On the other hand electrons can be made to travel at very high speeds and it is found that their mass does indeed increase in just the fashion that the theory of relativity predicts. There is however, another aspect of the matter to which attention should be directed. The discussion above maintains that energy given to a moving body appears as an increase of mass ; nevertheless, when the body ceases to move it gives up its energy and the additional mass disappears. The whole process seems to be a very temporary one. Not every case is as temporary as the one we have been discussing, for if we give heat energy to a body, we increase the velocity of motion or vibration of the atoms of the body, and to this increase in velocity there must correspond an increase in mass. But the change is very small. If we heat 1 gram of copper by 100°C. we need about 9 calories of heat energy, or expressed in mechanical units we need nearly 40 joules ; this amount of heat energy will increase the mass of the copper by a little more than one part in three million million.

(2) *Conversion of mass into energy.*

These increases in mass are so small that the whole phenomenon might be regarded as trivial were it not for the attention that has been directed to the very large amounts of energy that could be made available if mass were converted into energy on any appreciable scale. If a mass as small as 1 mg. is changed into energy the amount released is no less than $9 \times 10^{10}$ joules or 25,000 kWh. Discussions along such lines lead to the conclusion that if we wish to obtain large amounts of energy we have only to arrange to convert mass into energy.

There is nothing false in this point of view, but it seems better to regard the mass energy relation in a rather different way. It should be realized that in any process at all in which energy is released, there is a corresponding decrease in mass. If we burn a quantity of carbon, the original mass of the carbon and the oxygen required to burn it is greater than that of the products of combustion, the difference being equal to the mass of the energy released in the reaction. Hence, in a closed system from which neither the products of combustion nor heat energy can escape, there is no change of mass arising

from chemical change. Further consideration of the matter shows that the mass energy relation no more tells us how to obtain energy from matter than does the first law of thermodynamics tell us how to turn heat into mechanical energy. Nevertheless, if heat is turned into work, the first law of thermodynamics tells us that for every calorie so converted 4.2 joules of energy are produced; it tells us nothing that helps us to decide upon a suitable method for such a production of mechanical energy from heat energy. The analogy with the mass energy equation is complete. If there is any kind of reaction which yields energy, and if eventually the energy is withdrawn from the products of the reaction, the products must then have less mass than did the materials from which they were formed. But the mass energy relation gives no indication as to which processes will yield large amounts of energy; to determine this other principles of physics must be applied. We should then say that because a certain reaction yields a large amount of energy there must be a considerable diminution of mass rather than say that there is a large yield of energy because of a considerable diminution of mass; it is true that one cannot occur without the other, but usually our ideas of physical processes are adequate to explain in terms of forces the reason for the release of energy.

As an example of the release of energy and the consequent diminution of mass, we may consider what happens when an $\alpha$ particle is emitted by a radioactive atom. For simplicity we suppose that the nucleus is so heavy that only the $\alpha$ particle has appreciable energy. At the moment of emission the $\alpha$ particle has a considerable amount of kinetic energy and in consequence its mass is greater than its rest mass; this state of affairs is not altered until the $\alpha$ particle loses some energy, for it is only then that it parts with some of its excess mass. This excess mass does not of course disappear; it is simply shared amongst a large number of atoms or molecules to which the $\alpha$ particle imparts its energy. Thus, some of the energy of the radioactive nucleus is converted into heat energy of molecules; that amount of energy caused the original nucleus to have more mass than the rest masses of the two particles into which it was transformed.

Viewed in this way, the mass energy relationship is important because it is one of the fundamental relations of physics. Its form was so long hidden only because it is difficult to communicate to a piece of matter, even to a very small piece, enough energy to make a measurable change in its mass. Nevertheless, a simple argument can be given to show that the absorption of light energy gives an increase of mass of the absorber.* This argument depends

* Compare "Atomic Physics", M.Born, (Blackie and Sons Ltd.), 1935, Chap. III, p. 46.

on a knowledge of the pressure of light and on the assumption that the emission of light within a closed system cannot give rise to a force on the system; it leads to the conclusion that on the absorption of energy E there is an increase in mass of $E/c^2$, i.e., to the mass energy relation. These considerations, and others like them, show us that energy has mass; this can also be shown by experiments on electrons or on very fast atomic particles.

## CHAPTER V

# OBSERVATION OF INDIVIDUAL ATOMS

(1) *Measurements of the properties of ionizing particles.*

Earlier chapters have described some of the basic information which became available within a period of about ten years after the discovery of radioactivity. At a very early stage radioactive phenomena were recognized as being atomic, and it was from this point of view that they were discussed by those working on them. Unfortunately atoms are very small and impossible to observe, and the progress in atomic physics depended vitally on the provision of methods which were capable of revealing the presence of an individual atom, or rather of the radiation emitted by it.

To measure the properties of radiations in quantity is fairly simple, even when the amount of radiation is small. Information was most readily obtained concerning the properties of $\alpha$ particles, largely because they ionized intensely, they travelled in straight lines and all the $\alpha$ particles emitted from a pure radioactive substance had almost the same range.* Information was first obtained by measuring directly, perhaps with a relatively simple gold leaf electroscope, the ionization produced by these particles. It should be realized that even this electrical method is comparatively sensitive, and is readily capable of detecting ionization currents of the order of $10^{-12}$ amp., i.e., about 6 million ions per second. Now as a single $\alpha$ particle will produce about $10^5$ ion pairs in its path in air, a matter of 1000 $\alpha$ particles per second gives rise to an ionization current that can be detected with an electroscope and is capable of reasonably accurate measurement with electrometers of the type that have long been available. Not only can we arrange to detect the arrival of a few $\alpha$ particles; it is not difficult to measure the relative ionization produced at different points along the range of a beam of $\alpha$ particles and to obtain information concerning the average number of ions produced by an $\alpha$ particle of given velocity of emission and the distribution of ionization along the path of this particle.

The $\beta$ particles were less easily investigated because of their variable range and their practice of travelling in tortuous paths. There was also a complication arising from $\gamma$ rays, which are emitted after the disintegration of some $\beta$ ray† emitting substances. These $\gamma$ rays are sometimes absorbed in the

* Compare Figs. 5 and 7 on pp. 34 and 35.

† The radiations from radioactive substances were once known as $\alpha$, $\beta$ and $\gamma$ rays. We now know that $\alpha$ and $\beta$ rays are particles, but the term "ray" is still used when it is unnecessary to emphasize the corpuscular nature of the radiation.

material of the β ray source, perhaps even by the electrons surrounding the nucleus from which they come, and as a result the source emits high energy electrons which are often difficult to distinguish from β particles arising directly from nuclear transformations. Nevertheless, by patient work much information was obtained about radioactive disintegration processes, and gradually a good deal of data became available concerning the emission energies of α particles, β particles and γ rays.

(2) *Scintillation method for detecting individual α particles.*

Many methods were developed for observing single fast particles, especially α particles. The first of these, which was extensively used by Rutherford in much of his work, was the scintillation method. When an α particle falls on a piece of zinc sulphide, it gives rise to a faint green flash. From multitudes of such flashes arises the green glow given by some luminous watches and clocks; in suitable circumstances a separate flash can be made visible for each α particle falling on a zinc sulphide screen. Experiments involving the use of zinc sulphide were carried out in some such way as this :—The screen was prepared by covering a piece of glass with a thin layer of small crystals of zinc sulphide, and this screen was viewed through a microscope of great light-gathering power. The observations were made in a darkened room; for the best results it was necessary that the observer should not begin his observations before his eyes were dark-adapted, the particles had to be arriving at a suitable rate which was about twenty per minute, and the observer required frequent rests to avoid making errors owing to visual fatigue. This arrangement made it possible to count the number of α particles hitting the zinc sulphide screen, and with it most important results were obtained. It is sufficient to mention that the investigations of the scattering of α particles by thin metal foils* depended wholly on this method of counting them. Fortunately physicists do not now have to carry out such painful experiments in order to obtain data concerning the emission of α particles. The scintillation method was of no use for counting β particles.

(3) *Expansion or Cloud Chamber.*

Most methods of detecting single particles from radioactive substances depend upon making use of the ionization that these particles produce. The available methods take a number of forms, not all of which are worth discussing fully here. The most beautiful of these methods, and in some ways the most powerful, is the cloud chamber or expansion chamber devised by

* These investigations were mentioned in Chap. 2, p. 16.

C. T. R. Wilson. This cloud chamber is a simple device which makes visible the paths of ionizing particles that pass through the chamber.

The construction of a simple form of cloud chamber is shown diagrammatically in Fig. 4. The chamber consists of a short glass cylinder with a sheet of plate glass sealed to its end; the movable floor of the cylinder con-

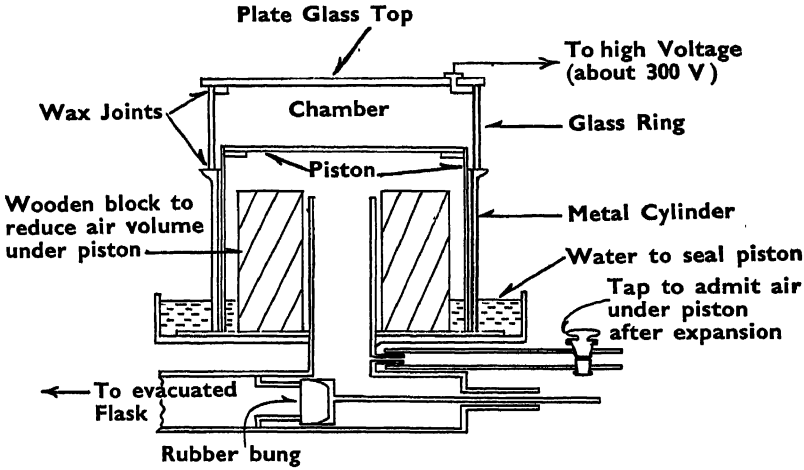


**Fig. 4.** Diagram of a simple type of Cloud Chamber. Expansion occurs when the rubber bung is drawn to the right so as to allow the air under the piston to flow into the evacuated flask. After the expansion, the bung is replaced, the tap is opened and, as air enters the space below the piston, this rises eventually to its initila position.

sists of a blackened plate which is part of a piston which makes the cylinder air tight and also enables the volume of the cylinder to be changed at will. For proper operation, arrangements must be made so that the piston can be rapidly moved downwards. Very often the gas in the cylinder is air, saturated with water vapour; initially the air may be at or near atmospheric pressure, and when the expansion occurs the movement of the piston is such that the height of the chamber is increased by about 30 to 33% of the initial height. The expansion of the air is rapid enough to be adiabatic so that the air in the chamber is suddenly cooled, and the water vapour in the air is greater in amount than the saturation value at the lowered temperature. As a result of the supersaturation of the air, water vapour condenses on anything that is available, and if any ions are present in the chamber water drops are

formed upon them. The water drops formed are not usually very large, but if they are suitably illuminated they can readily be seen and photographed. Unfortunately they do not long remain in the places in which they were first formed because the air in the chamber soon commences to warm up, and when this happens air currents destroy the cloud tracks.

In practical arrangements certain precautions are needed. In the first place the air in the chamber must be clean and free from traces of certain organic vapours. Furthermore, means must be adopted for dealing with any ions formed in the chamber before the expansion takes place; these may arise from radioactive sources which are being used near the chamber, from X rays or other penetrating electromagnetic radiation, or from cosmic rays. To remove these ions an electric field is maintained between the floor of the chamber and a metal ring on the plate glass cover, and this electric field sweeps away most of the unwanted ions formed before the expansion; naturally precautions are taken to minimize the ionization in the chamber during the period before the expansion, but it is not usually practicable to reduce this ionization to zero. The expansion should be made quickly, preferably in less than 0.1 sec.; immediately the piston has gone down, the ionizing particles are momentarily allowed to enter the chamber. There is a short period after the expansion when water drops will condense on any ions in the chamber, and this condensation process is so rapid that any ions then formed are fixed in their positions of origin by the growth of water drops around them. Ideally, then, the radiations to be studied should be allowed to enter the chamber only during this period. If the ion pattern is to be recorded by photography, a short flash of intense illumination is arranged to occur just after the radiation has entered the chamber and the water drops have condensed on the resulting

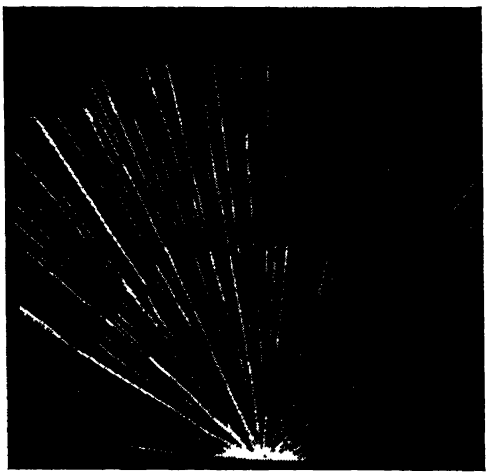

**Fig. 5** Cloud chamber tracks of $\alpha$ particles from ThC and ThC′.
(From *The Newer Alchemy*, Rutherford, Cambridge University Press.)

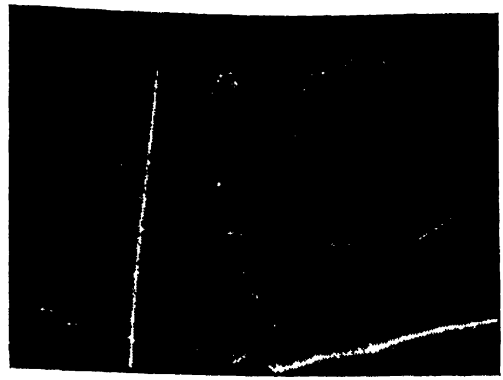

**Fig. 6.** Cloud chamber tracks in hydrogen. The two dense tracks are caused by $\alpha$ particles, the other tracks by $\beta$ particles.
(From *Radiations from Radioactive Substances*, by Rutherford, Chadwick and Ellis Cambridge University Press.)

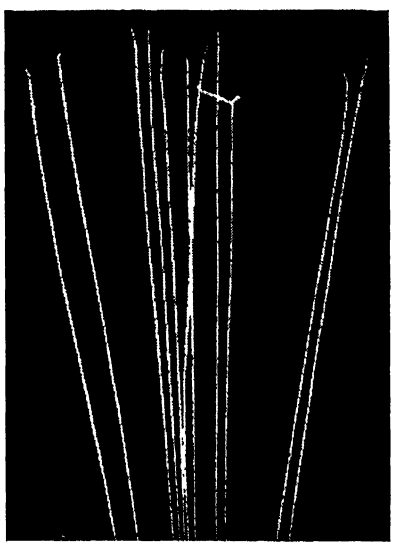

**Fig. 7.** Cloud chamber tracks. The last 3 cm. of the tracks of 8.6 cm. $\alpha$ particles from ThC′. This picture shows small variations in $\alpha$ particle ranges. The particle making the third track on the right collided with a heavy atom, probably a nitrogen atom.
(From *Radiations from Radioactive Substances*, by Rutherford, Chadwick and Ellis, Cambridge University Press.)

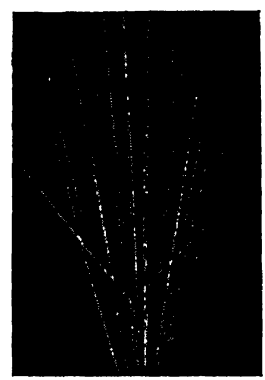

**Fig. 8.** Cloud chamber photograph showing the result of a collision between an $\alpha$ particle and a helium atom.
(From *Radiations from Radioactive Substances*, by Rutherford, Chadwick and Ellis, Cambridge University Press.)

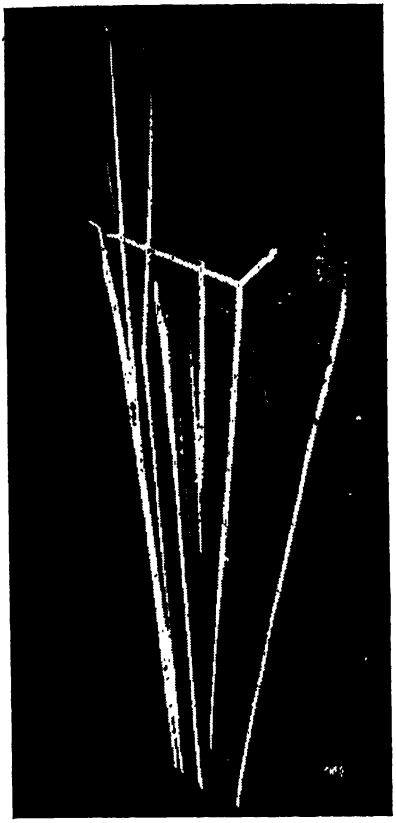

**Fig. 9.** Cloud chamber photograph. The fork arises from a collision between an $\alpha$ particle and an oxygen atom.
(From *The Newer Alchemy*, Rutherford, Cambridge University Press.)

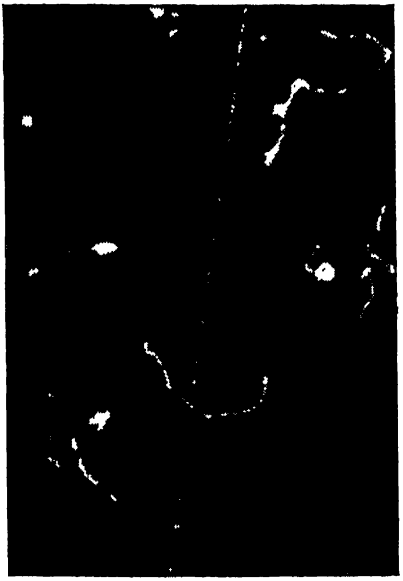

**Fig. 10.** Cloud chamber photograph showing the feeble ionization produced by a high speed electron with a straight path, and the curved paths and denser ionization arising from slower electrons.
(From *The Newer Alchemy*, Rutherford, Cambridge University Press.)

ions. Shortly afterwards the piston is raised and preparations are made for the next expansion.

It is difficult to give an adequate description of what is seen in an expansion chamber; even Figs. 5 to 10 give an impression rather different from the one obtained by observing a chamber in operation. The actual tracks are

hardly as white as they appear in a photograph, but their existence in three dimensions gives information which is not recorded in a single picture. These photographs bear out our description of $\alpha$ and $\beta$ particles. After seeing such photographs as are given here one believes that $\alpha$ particles produce intense ionization along paths which are approximately straight and of uniform length; one also appreciates what happens when an $\alpha$ particle is deflected by making a close collision with a heavier atom. It is clear, too, that when a $\beta$ particle* moves in a straight path it produces few ions per cm. of path; near the end of the track of a $\beta$ particle more ions are produced and the path is tortuous. In order to obtain a general picture of ionization processes, nothing is more instructive than to make observations with a Wilson cloud chamber.

Although the whole affair sounds simple and is capable of giving most valuable insight into phenomena connected with the passage of fast particles through gases, and at the same time most beautiful pictures of these phenomena, it is not easy to operate an expansion chamber so as to obtain records of the highest quality. The great wonder is that C. T. R. Wilson was successful in showing that the arrangement would work and in obtaining with this apparatus records of such quality as have rarely been equalled since.

Although, as we have seen, the apparatus is capable of showing in detail the whole course and intense ionization of an $\alpha$ particle, it has unfortunately two serious disadvantages. The shallowness of the chamber and the necessity for confining the observations to the relatively small region near the object plane of the camera are sometimes serious limitations. Far more serious is the slowness with which observations are made. Although automatic arrangements have been made for photographing what occurs in an expansion chamber, these do not take more than a few photographs a minute. Any increase in the rate of operation of the cloud chamber is accompanied by a marked deterioration in the quality of the tracks. When one remembers that an expansion chamber will make visible the radiations entering the chamber during a period of about 0.1 second at the time of expansion, one can appreciate that many thousands of photographs must be taken, and much time must elapse, before a few records are obtained of some rarely occurring event. Nevertheless, the expansion chamber continues to be used because of its ability to record the whole track of an ionizing particle, and in this respect it is paramount amongst the devices which can detect single particles. It has proved itself time and again by its usefulness in providing unassailable evidence for the existence of a new particle or of a new atomic reaction.

* The tracks of Fig. 10 are similar to what might be produced by $\beta$ particles although the electrons causing these tracks were not emitted as $\beta$ particles from a radioactive body.

(4) *The use of the photographic plate for recording heavy ionizing particles.*

Another device of much power is the photographic plate used as an indicator of the passage of heavy particles. A swift heavy particle has only a small range in a photographic emulsion, but after its passage and the subsequent development of the plate, a microscope will show where the particle has gone. The photographic plate is a kind of expansion chamber on a microscopic scale. The short ranges of the recorded particles are disadvantageous, but against that can be set the advantage that the photographic plate is sensitive to radiation for periods of the order of years, and with its help some rare processes may be simply studied. Furthermore, the examination of a single photographic plate may be incomparably more attractive than the necessary examination of thousands of expansion chamber photographs, when very few indeed show the particular type of phenomenon which is sought.

(5) *Counters: Linear amplifier and Geiger Counter.*

Despite the power of the methods just described, much modern work is carried out with various types of " counters ", instruments which can record on a dial the arrival of a particle to which the active part of the counter is sensitive. Two types of counter are in common use, the linear amplifier type and that using a Geiger-Müller tube.

The linear amplifier counter is very simple in principle and is appropriate to the observation of $\alpha$ particles, protons* or swift particles of higher masses. All of these ionize intensely as they pass through air at ordinary pressures, and even in a path of a few millimetres length an appreciable number of ions is formed; if the negative ions are collected on an electrode connected to the input of a high gain valve amplifier, it is possible to arrange that the passage of a heavy ionizing particle in the neighbourhood of the collecting electrode gives rise to a momentary pulse of current in the output circuit of the amplifier. This pulse, the height of which is proportional to the number of ions reaching the collecting electrode—hence the term " linear " amplifier—can be passed to a galvanometer, the response of which can be recorded on sensitive paper; or it may be used to give a visible displacement of the spot of a cathode ray tube; alternatively the pulse may be used to actuate a mechanical register by which the number of pulses is recorded. When suitable precautions are taken these counters can easily be arranged to record particles arriving at average rates of 100 per second or more. The information which was acquired in a few days as a result of scintillation counting can be obtained by modern valve amplifiers and mechanical registers in the

* A proton is a swift hydrogen nucleus. See Table of Particles and Radiations at the end of the book.

course of a few minutes. It is not necessary to dwell on the consequences of the development of such devices as these, for it is obvious that they have contributed in no small measure to the recent increased rate of progress in atomic research. Although it is not appropriate to give here any extensive details of the amplifiers used in these counters, it may be of interest to mention that they usually incorporate negative feed-back and have sufficient gain to show on a cathode ray tube the "electrical noise" in the grid and anode circuits of the first valve of the amplifier. The choice of this first valve is important, as its noise level determines the smallest amount of ionization that can be detected in the output of the amplifier; the valve chosen as the first one is operated in such a fashion as to give maximum signal to noise ratio in the output of the amplifier.

We now consider the Geiger-Müller tube,* an instrument which responds to fast electrons such as β particles, the electrons resulting from the interaction of radiation with matter or those from a suitable discharge tube or electron accelerator. These particles produce too few ion pairs to give adequate response from a linear amplifier, and recourse is had to a process which even to-day is not completely understood, that of ionization by collision. A typical Geiger-Müller tube consists of a glass envelope within which is a thin wire surrounded by a cylindrical metal electrode; in the space between these two electrodes is a gas at low pressure. When a sufficiently high electric field is established between these electrodes, a very sensitive condition can be attained in which apparently a single ionizing electron within the tube is able to produce a small but appreciable discharge between the electrodes. The initial ionization of the particle is multiplied by collision, a discharge starts and after a small quantity of electricity has been transferred from one electrode to the other the discharge ceases. After a short time—between perhaps 10 and 100 microseconds—the tube has recovered its sensitive condition and is ready to respond to another particle. The amount of electricity transferred by the discharge is not great enough to actuate a recording meter, but this can readily be achieved after a small amount of amplification. The Geiger-Müller tube is thus capable of high operating speeds; it is very much used when making measurements on properties of β particles or of other high speed electrons, even though the tube may not record every particle which passes through it. The type of Geiger-Müller tube described above is one of the simplest; the actual form chosen in any given case will depend very much on the particular circumstances of the experiment being performed and on the properties and energies of the particles about which information is required. In any case the tube must be arranged so that the electrons being investigated traverse the space between its electrodes.

* This tube is often called a Geiger counter or a G-M counter.

The amplifier used with a Geiger-Müller tube is much simpler than a linear amplifier. The voltage pulse from the tube is relatively large and bears no proportionality to the ionization which gives rise to it; consequently, the amplifier need not be linear nor need it give large gain. In many cases, however, it is advantageous to use amplifying circuit constants so chosen that the amplifier yields a steep-fronted narrow pulse on every occasion on which the Geiger-Müller tube operates.

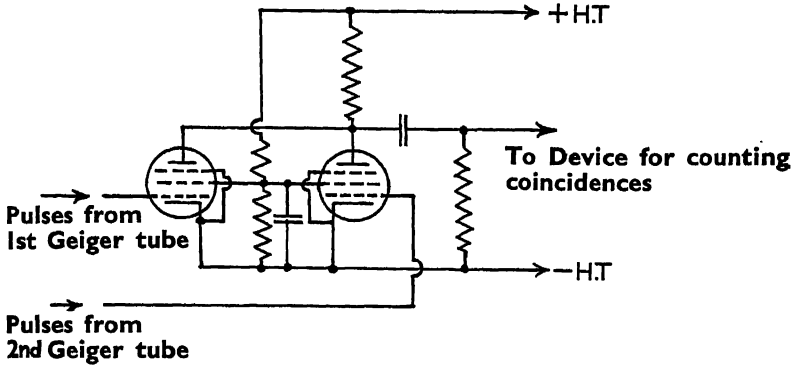


**Fig. 11.** Circuit used in a counter for recording the coincidences of two Geiger-Müller tubes.

In concluding this chapter, it is appropriate to mention a technique which can be used to determine whether two events happen simultaneously or consecutively. Fortunately the valve circuits used with counters are very easily adapted to giving this information; used in this way they are known as coincidence counters. Those who are familiar with wireless technique may be interested to see the details of the very simple arrangement used to indicate coincidences between pulses coming from two or more Geiger-Müller tubes. In Fig. 11 is a circuit diagram of the simplest type of arrangement in which a valve circuit responds only when there is a coincidence between the pulses arising in two different circuits. These pulses must both be negative pulses of the same shape; each circuit supplying them is connected to the control grid of a pentode valve. These pentodes have very little bias on their grids, but the total anode current is limited because the anodes are connected in parallel and are fed from the high tension supply through a resistance which drops the anode potentials to within a few volts of the cathodes. This resistance must be of sufficient magnitude to ensure that, as

long as the grid potential of one valve retains its normal value, the anode potential does not rise by more than a negligible amount; thus not until negative pulses arrive at both grids simultaneously, or within a time interval less than the resolving time of the coincidence counter, will the anode potentials rise by a sufficient amount to record a coincidence. This resolving time, which depends on the values of the components used in the circuits, can be made as short as 1 microsecond or even less. Coincidence counters of short resolving times have proved invaluable in the investigation of phenomena in which two or more atomic processes occur within a very short interval of time.

Further information concerning the subject matter of this chapter will be found in the books on radioactivity listed at the end of Chapter 3 and in " Electrical Counting ", W. B. Lewis, (Cambridge University Press).

## CHAPTER VI

# NUCLEAR PHYSICS : 1919—1930

(1) *Early attempts to cause nuclear transformations using α particles.*

The α particles from radioactive substances are emitted with very large initial energies. The most energetic α particles arise from ThC′, a radioactive substance of very short half life which is always present in preparations of thorium C ; these α particles have an energy of 8.76 MeV.* Even the shorter range α particles from radon and radium A have energies in excess of 5 MeV and the energy of the α particles from radium C′ exceeds 7.5 MeV. That these energies are large may be realized by noting that the average energy of an atom in a mass of helium gas at a temperature of $5 \times 10^{10}$ °C. is only of the order of 5 MeV.

It was early suggested that the large energy content of α particles was possibly sufficient to bring about atomic transformations, or disintegrations as they are often called, and a number of experiments were made to test this possibility. In typical experiments various substances were mixed with radon so that they were subjected to α particle bombardment by the α particles from radon, radium A and radium C′. After the radon and its immediate short lived products had disappeared, the substances under investigation were carefully examined for the presence of the products of disintegration ; none was definitely found. Cameron and Ramsay, who performed such experiments in 1907, first announced positive results, for it was believed that under α particle bombardment water was transformed into neon and argon ; later on, however, it was established that the α particle bombardment simply liberated chemical elements which were initially present in the substances being bombarded. As subsequent events have shown, the idea underlying these experiments was right, but the methods of detection were insufficiently sensitive to show whether or not atomic disintegration was achieved.

(2) *Rutherford's disintegration of nitrogen.*

Atomic disintegration by α particles was first detected in 1919 by Rutherford in the following circumstances. He had made some experiments on the effects of collisions between α particles and other atoms, especially hydrogen atoms. He had shown that what occurred experimentally was in accord with theoretical predictions, and that when a hydrogen atom was struck by

* For millions of electron volts we write MeV.

an α particle it was possible for the struck particle to have a velocity and range greater than that of the striking α particle. This observation was of vital importance because most radioactive sources of α particles contain traces of grease or other hydrocarbons, and from these protons are ejected. Whenever long range particles are found to arise from a source of α particles, it must first be assumed that these are protons which have suffered nearly head-on impacts with the α particles produced by the source. Now Rutherford had found, as had been predicted from theoretical considerations, that these "knock-on" protons had a range of about four times that of the α particles giving rise to them. This means that a source of radium C′, which gives α particles of 7 cm. range in standard air, will not give any long range protons which exceed 30 cm. in range, and if suitable precautions are taken the source can be prepared so as to give only a very few protons of shorter ranges.

Rutherford had been examining the long range particles from a radium C′ source. This α particle source was mounted within a box which could be exhausted or alternatively filled with any desired gas. A diagram of the apparatus is shown in Fig. 12. Opposite the source D was a thin silver foil

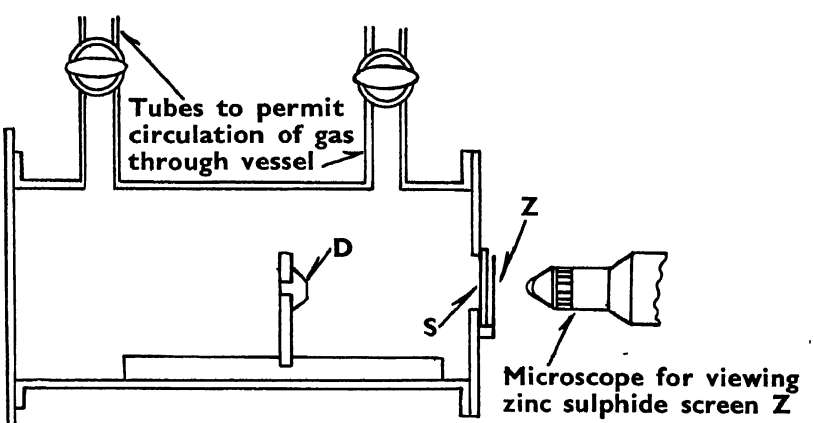


**Fig. 12.** Rutherford's apparatus for observing protons arising from α particle disintegration of nitrogen.

S, which served to close the box and also to allow the passage of any α particle which had a range in air in excess of 6 cm. Outside the box was a zinc sulphide screen Z, on which could be observed the impact of any particle

which was energetic enough to pass through the silver screen and any other absorbing material which was placed between the silver foil and the scintillation screen. When the box was filled with nitrogen, scintillations were observed on the screen even when the absorbing material between the source and the screen was much in excess of that necessary to prevent the $\alpha$ particles from reaching the screen. These scintillations might have arisen from hydrogenous material in the source—and, indeed, the particles causing the scintillations had about the same ranges as would be expected of particles of this origin—but this was not the correct explanation, for the scintillations disappeared when the gas in the box was replaced by oxygen or carbon dioxide. Measurements of the effect produced when these particles were deflected by a magnetic field indicated that they were protons. And yet they were produced when $\alpha$ particles bombarded nitrogen atoms. The method was both simple and sensitive, for calculation and the observed scintillations showed that only about one $\alpha$ particle in one million gave rise to a proton. Not only, then, did the experiment prove that an atomic transformation was occurring, but it showed why Ramsay's experiments gave negative results; the disintegration process occurred so rarely that with the $\alpha$ particle sources available there was no reasonable hope of collecting sufficient of the products of the disintegration to make possible a chemical determination of their nature or even to allow their presence to be detected.

Further careful experiments showed that the disintegration protons produced by $\alpha$ particle bombardment of nitrogen had appreciably longer ranges than protons arising from collisions between $\alpha$ particles and hydrogen atoms. The sensitivity of this method of detecting disintegrations arises almost entirely because of the very long range of the ejected protons. Many elements were examined with the use of similar experimental methods, and it was found that boron, nitrogen, fluorine, sodium, aluminium and phosphorus were disintegrated on $\alpha$ particle bombardment and gave rise to very long range protons. Little could be said with certainty about other elements except that if they were disintegrated the protons produced were not sufficiently many or of sufficiently long range to be distinguished from those arising from impacts between $\alpha$ particles and hydrogen atoms.

As the following considerations show, it was useful, when using materials that did not give long range disintegration protons, to look for short range protons in a direction at right angles to the incident bombarding $\alpha$ particles. As theoretical considerations showed that no proton arising from the $\alpha$ particle source could be deflected through 90°, it was clear that any protons observed would establish the occurrence of a disintegration process. Furthermore, as observation had shown that disintegration protons from aluminium,

and from other elements as well, were emitted in all directions relative to the bombarding $\alpha$ particles, there was some assurance that, if disintegrations occurred upon $\alpha$ particle bombardment, an appreciable number of protons would be observed in the experimental arrangement proposed. Consideration of the possible origins of particles ejected at right angles to the direction of the incident $\alpha$ particles made it apparent that any particle which exceeded the range of the $\alpha$ particle and which was observed could only arise from a disintegration process. A slight complication, which is easily seen to be unimportant, arose from the fact that the source of $\alpha$ particles, RaC′, although ejecting most of them with a velocity which gives them a range of 7 cm. in air, ejects a few long range particles with ranges up to 11 cm.; but in the experiments being discussed, there was a negligible chance of such particles being scattered in such a direction as to make them apparent on the observing screen. Such experiments, as well as those described earlier, showed that with the exception of carbon and oxygen all the elements in the atomic table from boron to potassium were disintegrated on $\alpha$ particle bombardment. The experiments also showed that fast $\alpha$ particles were more effective in causing disintegrations than were slower ones. In particular, for $\alpha$ particles having a range of 7 cm. in air, it was estimated that every million particles produced about 20 disintegrations on being absorbed in nitrogen, about half that number when aluminium replaced nitrogen, and only about one disintegration in heavier elements such as chlorine, argon and potassium.

The disintegration process is popularly known as "atom splitting" because of the appearance of the fast proton which is ejected as a result of $\alpha$ particle bombardment, but despite this description it has been established that when nitrogen is disintegrated a proton is ejected and the $\alpha$ particle and what remains of the nitrogen nucleus form a single entity which is more massive than the nitrogen nucleus. This may be shown by the following equation:

$$He_2^4 + N_7^{14} = H_1^1 + O_8^{17}$$

On the left side of this equation we have symbols for the bombarding $\alpha$ particle, a helium nucleus of mass number 4 and atomic number 2, and for the struck atom, here a nitrogen atom of mass number 14 and atomic number 7. After the reaction we have, as is stated by the symbols on the right side of the equation, a fast proton of mass number 1 and atomic number 1 together with an oxygen atom which has atomic number 8, as indeed all oxygen atoms do, and the rather unusual mass number of 17.* It will be noted

* There is no direct evidence to show that $O^{17}$ results from $\alpha$ particle disintegration of nitrogen, but in addition to the evidence discussed below there is indirect evidence that leaves no room for doubt.

that the subscript numbers are the nuclear charges and add up to 9 on each side of the equation, and that the upper numbers are the mass units and add up to 18 on each side of the equation. Equations like these are frequently used in the discussion of nuclear reactions, and although they are sometimes written a little differently from the equation above, they must always satisfy the condition that the total mass number and the total atomic number are the same on each side of the equation.

Let us discuss the experimental evidence which shows that the equation above is the correct one. That protons are ejected was established by Rutherford's disintegration experiments; the formation of $O^{17}$ was more difficult to prove. The necessary evidence was provided in 1925 by Blackett, who carried out experiments with an automatic Wilson cloud chamber. He arranged to "fire" into the chamber the $\alpha$ particles from thorium C; in the chamber was a gas consisting of 90% nitrogen and 10% oxygen together with sufficient water vapour to saturate it. About 23 000 photographs were taken, and on an average there were 18 $\alpha$ particle tracks per photograph; two thirds of the tracks were made by 8.6 cm. $\alpha$ particles from ThC′ and the remainder were made by the 4.8 cm. particles from ThC. The work of taking these photographs, and the careful examination of them, was a task of considerable magnitude, but very interesting results were obtained. Besides a large number of forked tracks arising from close collisions between $\alpha$ particles and the heavier gas atoms in the expansion chamber, there were eight examples of a different type of process. In each case there was seen what was undoubtedly a proton originating from a point on the track of an $\alpha$ particle. Seven of these protons were ejected in the same general direction as that of the bombarding $\alpha$ particle, but in one case the proton was ejected in the backwards direction. Now beyond the point of origin of the proton there was only one other track; apparently the bombarding $\alpha$ particle entered the nitrogen nucleus and the resulting atom, which had mass number 18 and atomic number 9—it was fluorine of mass number 18—immediately disintegrated to give the proton and $O^{17}$. The disintegration process is then one of exchange in which a heavy projectile enters a nitrogen nucleus where it remains; a lighter particle is ejected. All the data which could be obtained from Blackett's photographs were consistent with this hypothesis, and the process just described is regarded as typical of disintegrations which are caused by $\alpha$ particles and result in the emission of fast protons. In Fig. 13 is a reproduction of one of Blackett's nitrogen disintegration photographs.

Blackett's photographs made possible a determination of the energy

balance occurring in the disintegration process.

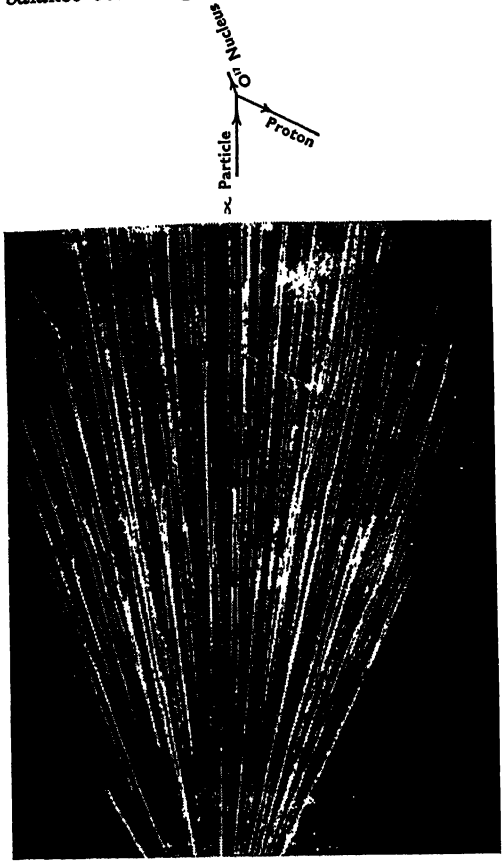


**Fig. 13.** Cloud chamber photograph showing $\alpha$ particle disintegration of nitrogen. The key diagram assists in an interpretation of this photograph. (From *The Newer Alchemy*, Rutherford, Cambridge University Press.)

The results were not very consistent, but they showed that the energy of the proton and the $O^{17}$ nucleus was some 20% less than that of the incident $\alpha$ particle. In the case of the disintegration of aluminium, however, the energy resulting from the disintegration process was found to be greater than that of the incident $\alpha$ particle so that the experiments with aluminium represent the first case in which man was able to arrange an experiment giving a few instances of a process in which atomic energy was released. Admittedly only a negligible fraction of the $\alpha$ particles used were productive in this way; most of them simply failed to hit the very small target represented by the aluminium nucleus and wasted their kinetic energy in collisions with the outer electronic structure of the atoms amongst which they moved.

One cannot consider these experiments without being struck by the simplicity and sensitiveness of Rutherford's experimental technique. It is amazing that progress in the development of nuclear physics should be made by carrying out experiments which succeed on only one occasion in one hundred thousand.

(3) *Accurate measurements of atomic masses.*

During the period when artificial atomic disintegrations were being investigated, Aston was making accurate measurements of the relative masses of the atoms of most of the elements. His line of investigation arose from the earlier work of J. J. Thomson which resulted, as already described, in the discovery that neon consisted of two isotopes of masses 20 and 22; it was clearly desirable to see whether all elements consisted of isotopes having masses which were apparently integers. Aston devised new apparatus, capable of comparing atomic masses with an accuracy of about 1 part in 1000. This apparatus made use of means for producing high speed positive ions of the element under investigation; these ions were passed through electric and magnetic fields so disposed as to bring to one point on a photographic plate all ions with the same ratio of charge to mass. As every ion carries one or at most a very few electronic charges, it is possible to use the apparatus for the comparison of masses. For this reason Aston called this device a mass spectrograph. With it he reached the conclusion that if the oxygen atom was given the mass of 16 all atoms but those of hydrogen had masses which were whole numbers. By assuming this whole number rule, which in fact his apparatus was incapable of verifying exactly, and by making additional use of his mass spectrograph measurements to determine the relative abundance of isotopes of an element, Aston was able to deduce the chemical atomic weights. Such atomic weights, which involve the properties of materials in bulk, had been determined with great accuracy from experiments made with the naturally occurring mixtures of isotopes. In some cases Aston's measurements gave atomic weights which were close to the chemical ones, but as this did not occur in every case it became apparent that the hypothesis underlying his determination of chemical atomic weights was unjustified. It is now certain that atomic masses are not identical with mass numbers, but it was not only for this reason that Aston's measurements did not give the atomic weights that had been determined by the chemists.

As is well known the chemical atomic weights are relative numbers only and take their accepted values when the weight chosen for natural oxygen is exactly 16. Aston also chose 16 as the atomic mass of the oxygen atom, for when he took this step he did not realize that his oxygen was not the same as the chemist's oxygen. Natural oxygen is mostly $O^{16}$ but there are isotopes $O^{17}$ and $O^{18}$ which are present in small amounts. When, for example, the mass spectrograph is used for a determination of the atomic mass of fluorine, an element which has only one naturally occurring isotope, the mass of a fluorine atom is compared with that of an atom of $O^{16}$; but the chemist has compared the mass of millions of fluorine atoms with that of the same number of

natural oxygen atoms, some few of which are $O^{17}$ and $O^{18}$ atoms. Thus the chemical atomic weight of fluorine is lower than the atomic mass of the fluorine atom. To state the difficulty in another way, we can say that on the basis of chemical atomic weights pure $O^{16}$ would have an atomic weight just less than 16; in fact its value would be 15.9963.

The discovery of the existence of $O^{18}$, which is the more plentiful of thetwo rare isotopes of oxygen, had an important consequence. When oxygen was believed to be a single isotope, the mass of $O^{16}$ was compared by the mass spectrograph with the mass of $H^1$. The result obtained gave the mass of hydrogen as 1.00778, agreeing closely with the accepted value of the chemical atomic weight of hydrogen, viz., 1.00777. When oxygen was known to contain appreciable amounts of $O^{18}$, it was apparent that natural oxygen was heavier than pure $O^{16}$; if the ratio natural oxygen : natural hydrogen was in fact the same as $O^{16}$ : $H^1$ as determined by the mass spectrograph, natural hydrogen was heavier than $H^1$ and hydrogen must contain a heavy isotope or isotopes. As appeared later, Aston's mass of $H^1$ and the chemical atomic weight were both in error, and although hydrogen did contain a heavy isotope, it was present in smaller amount than was at one time anticipated; nevertheless, direct evidence for the existence of $H^2$ was sought and found, and eventually methods were devised for separating this hydrogen isotope from water. As water made from this hydrogen isotope is more dense than ordinary water, it is known as heavy water; the $H^2$ isotope of hydrogen is called heavy hydrogen or deuterium and is represented either by $H_1^2$ or $D_1^2$. The early methods of preparing heavy water were troublesome, but they nevertheless made it possible to obtain commercially, though at great cost, small quantities of this material. Deuterium is of great importance in nuclear physics and as we shall see later in the production of atomic power. The war-time interest of the Royal Air Force in the Norwegian heavy water plant must be attributed to the belief that the deuterium being separated there was destined for use in Germany in the preparation of material for atomic bombs.

(4) *Atomic masses and stability of nuclei.*

Further experiments with improved apparatus were needed to provide more accurate values of atomic masses and to-day the modern mass spectrograph, which continues to compare atomic masses by passing positive ions through electric and magnetic fields, is capable of giving values in close agreement with those obtainable by other methods. These precise atomic masses are of value in a discussion of the stability of atoms. As the actual values of the atomic masses are very close to the atomic mass numbers, it is useful to consider a quantity which may be called the mass defect, that is the mass by

which the atomic mass of an element exceeds* its mass number. Alternatively, we may usefully talk about the packing fraction of an atom, this quantity being defined as the mass defect divided by the atomic mass number. We can give a physical significance to these terms : the mass defect of an element is the amount of mass which would disappear if the element was broken up into particles, each with one unit of mass, that is with a mass of $\frac{1}{16}$ of the $O^{16}$ atom. Where the packing fraction is negative it is the average amount of mass lost for each particle of mass unity required to form the element in question. As is seen from Figs. 14 and 15, packing fractions are large and positive for the light elements, are negative and between 0 and $7.5 \times 10^{-4}$ for elements with mass numbers between 16 and 166 and thereafter are positive and quite small until the heavy radioactive elements are reached. By using the mass energy relation, we find that a packing fraction of $10^{-3}$ corresponds to an energy per particle of about 0.9 MeV. If then an atom of mass number 60 with a packing fraction of $-7 \times 10^{-4}$ could be made from particles with mass unity, there would be liberated for each particle used an energy of about 0.63 MeV. On the other hand, if we assume that the same atom is built up from particles having the mass of the hydrogen atom, the energy liberated will be very much more and will in this case amount to nearly 8 MeV per particle. In fact we don't make atoms up in this way, but the supposition is of some significance for the energy liberated in the assumed synthesis may give us some idea of the amount of energy needed to split up the atoms that are at our disposal. When account is taken of the fact that the radioactive

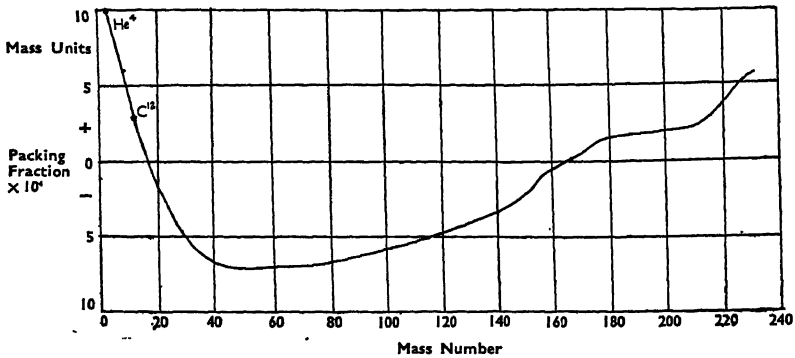


**Fig. 14.** Packing fractions of stable elements.[1]

* Although it is illogical, an atom like hydrogen with a mass greater than its mass number is usually regarded as having a positive mass defect.

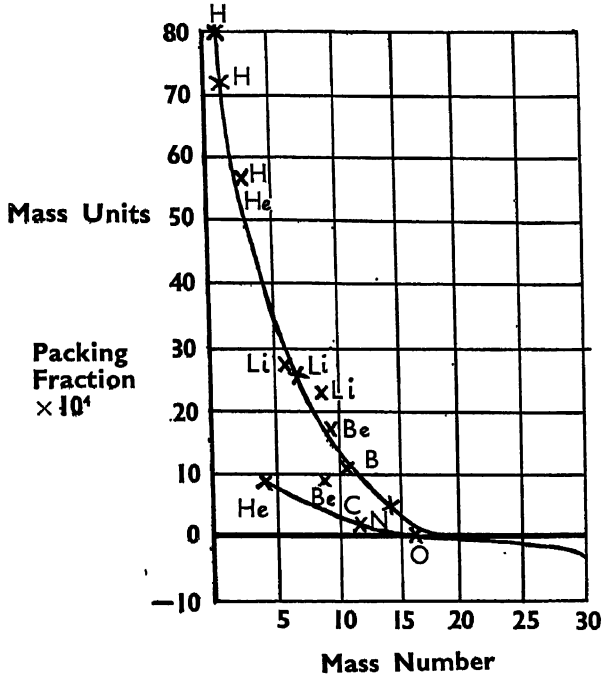


**Fig. 15.** Packing fractions of light elements.

atoms not only split up naturally but liberate considerable amounts of energy in doing so, it is apparent that the forces that hold atoms together are not so strong as would be anticipated if atoms were constructed from particles having the mass of hydrogen atoms. That $\alpha$ particles, rather than protons, are emitted from some radioactive elements is in accord with this conclusion.

However this may be, the relative stability of atoms is likely to be indicated by the value of the packing fraction, and on this basis both the light elements and the very heavy elements might be expected to be the least stable. It is not supposed that there is any precise connection between packing fraction and stability, although it is indeed the case that the heavy elements disintegrate spontaneously, and that many of the light elements are those most easily disintegrated by $\alpha$ particle bombardment. Nevertheless, as we shall see

later, accurate determinations of atomic masses were of much more value than in their application to this rather hypothetical consideration of the structure and stability of the atom.

(5) *Evidence in favour of the identity of all atoms of given atomic number and mass number.*

From the time of the discovery of the neon isotopes, it was assumed that neon was made up of two classes of atom, and that every atom of one class was identical with every other atom of that class. As it turned out, the development of the technique of measuring the masses of atoms served to confirm this early belief. As far as could be determined, every atom with given atomic number and mass number had the same mass as every other atom. There was no evidence of a range of masses amongst the atoms of one isotope of a given element.

This piece of information was in accord with what was to be expected from a study of $\alpha$ particle emission from radioactive elements. For here every $\alpha$ particle was emitted with the same energy, and as every $\alpha$ particle appeared to have the same mass the emission of an $\alpha$ particle from any atom of a given radioactive substance resulted in a constant reduction of mass of the parent. The obvious assumption, indeed the only satisfactory one, was that all atoms of both parent and product were identical. Information concerning $\beta$ ray emission did not confirm this view, for not all $\beta$ particles are emitted with the same energy, and from the point of view of the mass energy relation this might mean that not all atoms lose the same mass in a $\beta$ ray disintegration. Some of the missing energy is associated with the $\gamma$ rays that are frequently emitted after the emission of a $\beta$ particle, but even so it is clear from experiment that the mean energy emitted as $\beta$ and $\gamma$ radiation upon a given $\beta$ ray disintegration is not as great as the maximum energy with which a few $\beta$ particles are found to be emitted. It is felt that this is only an apparent difficulty which arises because of our inability to detect some of the energy which is released at the time of a $\beta$ ray disintegration, for it is believed that the atomic mass of a given $\beta$ ray emitting atom is decreased by a constant amount as a result of the emission of the $\beta$ particle. Because of the evidence from $\alpha$ particle emission measurements, and the confirming evidence from mass spectrograph experiments, it became accepted that all atoms of a given isotope were identical in mass and as far as was known in all other respects.

(6) *Nature of the Particles within the Nucleus.*

Nevertheless very serious difficulties were appearing in the light of growing knowledge of the nucleus. For many years it had been assumed that the nucleus was built up from protons and electrons. Neon with its atomic

number of 10 and mass number 20 was supposed to have a nucleus composed of 20 protons and 10 electrons. $Ne^{22}$ had two more protons and two more electrons. This assumption was made for two reasons. The only two fundamental particles then known were the proton and the electron. Furthermore, in the case of radioactive bodies the nucleus actually emitted electrons.

Now it was possible to make some estimate of the size of a given nucleus. This was determined from calculations based on the results of experiments in which some element, for example aluminium, was bombarded with $\alpha$ particles. These bombarding particles are sometimes deflected or scattered by the intense opposing field existing near the nucleus of aluminium. Experiments have shown that two point electric charges exert mechanical forces which are inversely proportional to the square of the distance between them; it was reasonable to calculate the distribution of scattered $\alpha$ particles on the assumption that their paths passed through an inverse square law electric field arising from the positively charged aluminium nucleus, and to compare the calculated and observed scattering patterns. As soon as the $\alpha$ particles approach sufficiently close to the nucleus they may be expected to experience different forces which will alter the pattern in which they are scattered. Experiments on these lines show that there is a breakdown of the inverse square law when an $\alpha$ particle makes a close approach to a nucleus; we regard the region of validity of the inverse square law as being outside the nucleus and the point at which the law just fails as representing the boundary of the nucleus. This interpretation is to be regarded as useful rather than precise, especially as head-on collisions with low speed $\alpha$ particles indicate a different nuclear size from that indicated by collisions with $\alpha$ particles of higher speed. Nevertheless it is found that for light elements the nucleus lies within a sphere of radius less than $10^{-12}$ cm. and even for heavy elements it is expected that the radius of the nucleus will not greatly exceed this quantity, although on this matter no experimental data are available, for $\alpha$ particles are not sufficiently energetic to penetrate so far into the nuclear field of an atom as heavy, for instance, as mercury.

The size of an electron is even more indefinite than that of a nucleus, but it possibly has a radius in excess of $10^{-13}$ cm. Although this is considerably smaller than the radius of a nucleus, it is not sufficiently small to make us happy with the idea of a nucleus of uranium, supposed to contain 238 protons and 146 electrons, all in the space of a sphere of radius about $10^{-12}$ cm. This is a difficulty, but in view of our lack of experience of particles as small as this when packed into small spaces, too much should not be made of it. The other difficulty is more troublesome to understand, but it was much more serious. The $\gamma$ rays are believed to arise in the nucleus; calculations

showed that if these radiations arose because of motions of electrons in the nucleus, they could not consist of radiations having discrete frequencies; on the contrary the motion of electrons would give rise to $\gamma$ ray energies and frequencies* which were distributed over some appreciable range. But experiment showed, with all the appearance of conclusiveness, that the $\gamma$ rays were very much "sharper" than if they were produced by the motion of electrons. Either there must be no electrons in the nucleus or they must behave abnormally in order to produce sharp $\gamma$ rays.

(7) *Theories of $\alpha$ particle emission.*

Finally there were serious difficulties about the emission of $\alpha$ particles from radioactive substances. The general position is quite easily understood by reference to the case of uranium I, which emits an $\alpha$ particle with the rather low energy of about 4 MeV. This energy is obviously obtained from the repulsion of the $\alpha$ particle by the electric field in the neighbourhood of the nucleus of the atom formed from the $\alpha$ decay of uranium I, and as the $\alpha$ particle carries two charges it must arise in a region where the electric potential is about $2 \times 10^6$ volts; since a small fraction of the initial potential energy of the electric charges is given to the recoiling nucleus, the $\alpha$ particle from a uranium I nucleus must arise at a point where the potential is slightly higher than this. In itself, this requirement can be accepted without much difficulty, although it involves the supposition that the $\alpha$ particles originate at a point about $6 \times 10^{-12}$ cm. from the centre of the nucleus, a state of affairs which seems to contradict the estimate of size given in the paragraph above. But despite the reasonableness of believing that $\alpha$ particles originate so far from the centre of the nucleus, there were even stronger reasons for the belief that they did not originate there. For when uranium is bombarded by 7.5 MeV $\alpha$ particles, which must be capable of probing the space from which the uranium I $\alpha$ particle would be supposed to originate, there is not the slightest evidence of the existence of any charged particle within this space. Indeed, the use of even the swiftest $\alpha$ particles available has given no evidence of anything but emptiness in the immediate vicinity of the uranium I nucleus.

Another difficulty was brought to light by the so-called long range $\alpha$ particles emitted by ThC. The radioactive transformations of this substance and of its immediate products are shown in Fig. 16. A source of ThC, which always contains ThC′, emits $\alpha$ particles which are mainly of ranges 4.8 and 8.6 cm., but in addition there are a few particles of range up to 11 cm. or more. As there are only about 250 long range particles for every million particles of range 8.6 cm. the long range particles were difficult to investigate. It was

* The relation between $\gamma$ ray energies and frequencies was given in Chap. 3, p. 24.

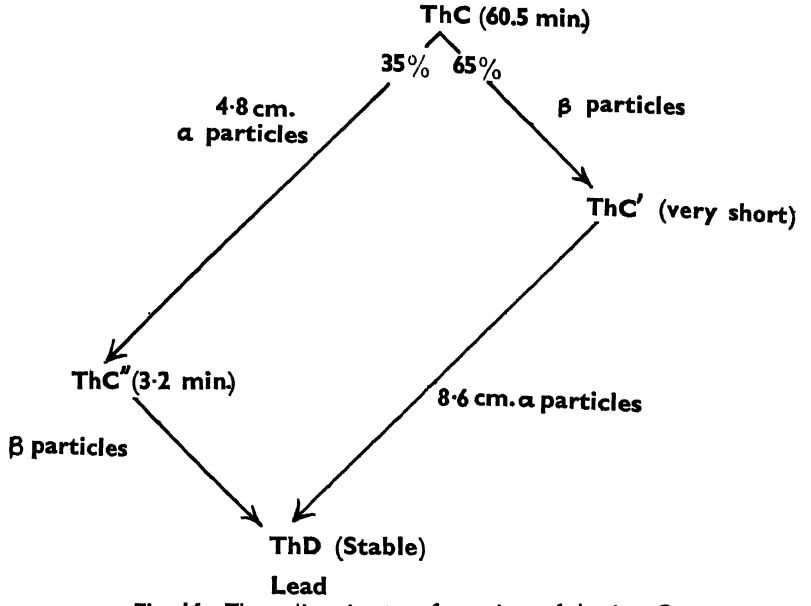


**Fig. 16.** The radioactive transformations of thorium C.

believed that they came, not from ThC itself, but from ThC′, a very short lived product formed after β decay of ThC and the source of the 8.6 cm. particles. Here then was a very unfortunate state of affairs in which it was apparently only an approximation to suppose that all α particles emitted by ThC′ had the same energy of emission. The position was not apparently improved by the discovery that the 4.8 cm. α particles emitted by ThC itself had not all the same velocity of emission. In this case, however, the range of velocity was quite small, and again only a few particles were in any but the most plentiful velocity group. The existence of these long range α particles and the discovery of the variety of ranges associated with the particles from ThC were profoundly disturbing, and doubt arose as to whether the accepted picture of radioactive phenomena was not falsely simple. Perhaps our ideas would have to be changed entirely before we were able to fit these new discoveries into the scheme of things. But, in fact, these small variations in α particle ranges were details that in the end gave reality to the existing views of the nucleus; in connection with them there was no revolution of thought.

These difficulties with α particle emission were the first to be explained. The explanation must be examined in some detail because of the light it throws on the structure of the nucleus of the atom. The position is best considered with the help of Fig. 17, which shows the potential energy of an α particle in the vicinity of a nucleus of atomic number 90, i.e., with a nuclear charge of 90 electronic units. As we approach the nucleus we find that the potential energy is inversely proportional to the distance from the centre of the nucleus*; experimentally this law of force is found to hold at all approachable distances in the vicinity of a heavy nucleus. In 1928 Gamow, and at the same time and independently Gurney and Condon, assumed that this law did not hold in the region of the nucleus to which the swiftest α particle cannot approach; they believed that at places nearer to the centre of the nucleus there were strongly attractive forces of very great power but of short

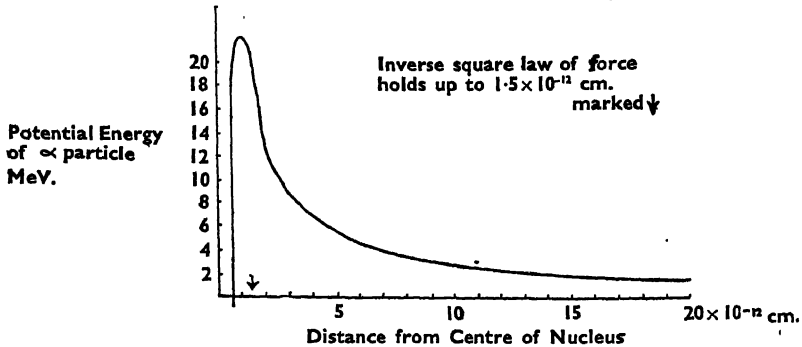


**Fig. 17.** Potential energy of an α particle in the neighbourhood of the nucleus of an atom of atomic number 90.

range. There was assumed to be a region where these short range attractive forces completely overcame any electrostatic repulsions, and where the potential energy of the α particle was small or even negative. This picture gives, in the neighbourhood of the centre of the nucleus, a potential barrier; the barrier is so high that no natural α particle is able to reach its top. Now the α particles of a radioactive substance are initially on the inside of the potential barrier; on the simplest view this barrier must be assumed to enclose the nucleus completely, and in consequence no α particle will be able to escape unless it either is able to pass over or through the barrier. As the α particles are emitted with energies smaller than 10 MeV they have

* The potential energy varies in this manner in a region in which electric charges experience an inverse square law of force.

insufficient energy to enable them to surmount the barrier; apparently escape is impossible even though it would be accompanied by release of energy. Consideration of the properties of the large material particles with which we make contact during our lives goes to confirm this view. But then modern physics has progressed because it has been realized that atoms and electrons do not behave as do ordinary material particles. The branch of mathematical physics which deals with the behaviour of an $\alpha$ particle in a nucleus is a complicated one which cannot profitably be discussed here. It must suffice to say that on the theory of Gamow the $\alpha$ particles are sometimes able to escape, even though they have not enough energy to go over the top of the barrier.

We may suppose the $\alpha$ particle within the nucleus to be in motion; it will then possess kinetic energy as well as the potential energy appropriate to its position. When the $\alpha$ particle is emitted, it will leave the nucleus with almost the same energy as that which it possessed when in the nucleus, and for this reason the speed of emission of an $\alpha$ particle, and its range in standard air, are related to its energy in the nucleus. On Gamow's theory, high energy $\alpha$ particles escape from a nucleus more readily than do $\alpha$ particles of smaller energy; consequently those substances which emit $\alpha$ particles of short ranges may be expected to have longer half lives than substances which emit $\alpha$ particles of longer ranges. The detailed theory gives a numerical relation between the half life of a radioactive substance and the energy of the $\alpha$ particles emitted by it; this theoretical relation is in close accord with experimental data. Although the theory gives no picture of the way the $\alpha$ particle passes through the potential barrier, it explains so much that its correctness can hardly be doubted; if improvements are needed they must be in matters of detail.

The theory explains the problem of the origin of the low energy $\alpha$ particles from uranium I.* These particles are within the potential barrier where of course they have no influence on the scattering of any $\alpha$ particles with which uranium is bombarded. Furthermore, this theory led to further experiments which served to explain the origin of the long range $\alpha$ particles. Careful measurements of the energies of these long range particles gave a value for the energy difference between such a particle and a normal 8.6 cm. $\alpha$ particle from ThC′. As this energy difference corresponded closely with the energy of a $\gamma$ ray, emitted by ThC′ just after its formation from its parent ThC, it became clear that the long range $\alpha$ particle must be regarded as an alternative to the emission of a $\gamma$ ray and then an $\alpha$ particle of normal range. Apparently, after ThC had emitted a $\beta$ particle, the resulting ThC′ nucleus

* See above, p. 54.

was sometimes left with excess energy which was either emitted as a $\gamma$ ray or was carried off as the additional energy of a long range $\alpha$ particle. This simple picture accorded closely with theory and with all the known facts, and it confirmed the growing belief that there was a constant amount of energy liberated when one radioactive nucleus transformed itself into another nucleus lower down in the radioactive series. This energy might appear in alternative forms, but if the various alternatives were compared, it would be found that in each the same amount of energy was liberated. A further simple example was provided by the $\alpha$ particles from ThC, where, as mentioned above, there are some few $\alpha$ particles which have ranges slightly different from the most usual range. It was found that these range differences arose because the $\alpha$ particle did not carry off with it all the available energy; some of this was left behind with the nucleus, and was subsequently emitted as a $\gamma$ ray. Such a theory must be tested against measurements of the energy emitted in the alternative processes; when this test was made there was found to be no room for doubt as to the correctness of the theory, for each of the possible processes liberated the same amount of energy.

For further information see the books on radioactivity listed at the end of Chapter 3 and "The Newer Alchemy", Rutherford, (Cambridge University Press); "Mass Spectra and Isotopes", F. W. Aston, (Arnold).

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## CHAPTER VII

# NUCLEAR PHYSICS 1932—1933

(1) *Review of outstanding discoveries.*

The period 1932-3 was remarkable for the discoveries then made in atomic physics. There were many reasons for the advances of these years and of them two are particularly important. The new quantum theory had been formulated and had become established, and in some cases its predictions suggested new experiments. Of greater importance, however, was the development in the experimental techniques of atomic physics, particularly in the direction of counting single ionizing particles by electrical means. Although these devices were discussed in Chapter 5 they had not reached a useful stage of development until about 1930, when they began to be used to an increasing extent and to assist greatly in the acquisition of knowledge of nuclear processes.

It is useful first to review the discoveries of the years 1932-3 and then to discuss their significance in some detail. In 1932 Cockcroft and Walton[1] described how lithium atoms were disintegrated when bombarded by high speed protons which had been accelerated after their formation in a discharge tube. Here was the first nuclear transformation process in which the fast particles as well as the disintegration process had been arranged by human agency.* In the same year Chadwick[2] announced the discovery of the neutron, a particle having a mass nearly the same as that of a proton but carrying no charge. The possibility of the existence of such a particle had been discussed much earlier by Rutherford[3], and its existence was known for some short time before its nature was appreciated. Also during 1932 Anderson[4] in U.S.A. discovered the positive electron, or positron as it is now usually called. The existence of this particle had been predicted as a result of theoretical studies, but although positrons are produced when penetrating $\gamma$ rays pass through heavy elements such as lead, they were first detected in expansion chamber photographs of cosmic rays. And finally during the year 1933 F. Joliot, and his wife Irene Curie, demonstrated artificial radioactivity[5]. They showed that it was possible to bring about atomic transformations which yielded radioactive forms of some of the common elements.

* Cockcroft and Walton's disintegration process had not occurred previously upon the earth. Many of Rutherford's disintegrations had been carried out in nature for millions of years.

All these discoveries have played an important part in the development of nuclear physics and indirectly in the discoveries which have led to the large scale release of atomic energy. Of the four discoveries, the most important was that of the neutron. The properties and behaviour of this particle are so vital to us that the next chapters must be devoted to their consideration; it is appropriate to mention here, however, that the discovery of the neutron made it unnecessary to believe that the atomic nucleus contained electrons. It was accepted immediately that the nucleus contained only neutrons and protons and that isotopes had the same numbers of protons but differed in mass because their nuclei contained different numbers of neutrons. We consider here the consequences of the other discoveries; we commence by describing the properties of the positron.

(2) *Positrons.*

This particle has a unit positive charge and the mass of an electron. It is formed when $\gamma$ rays traverse the intense electric fields which exist near the nucleus of a heavy element with a high atomic number. The energy of the $\gamma$ ray is used to create an electron pair—a positive and a negative electron—and to give these two components kinetic energy; the original energy of the $\gamma$ ray is greater than the kinetic energy of the electron pair by the amount of energy equivalent to the mass of two electrons. The positron has not a very long independent life; quite soon it combines with an electron and the kinetic energy of the positron and the mass of two electrons are converted into $\gamma$ rays. The process is interesting from many points of view, but particularly so to us because it provides a very good example of a way in which energy can be converted into mass and mass into energy. This process has an air of mystery about it, and it may suggest that it is possible to find means by which matter of every kind is converted into energy, with the result, as has already been pointed out, that there is a yield of large amounts of energy for the consumption of quite small amounts of mass. This, however, is never likely to be possible. As has already been explained, if the laws of physics show that a process will yield a certain amount of energy, we may use Einstein's relation to determine the resulting diminution in mass. The numerical relationships connecting mass and energy should not prompt us to believe that mass can be converted into energy whenever we wish.

(3) *Artificial disintegration of lithium.*

Cockcroft and Walton's experiment was in some respects a very simple one, but at the time at which it was performed the results were very surprising. It had been realized for some considerable time that fast protons might be

able to carry out atomic transformations, but most people assumed that energies of many MeV would be needed before such transformations could be effected. This belief was substantially correct, but there are cases in which much less energetic particles are able to bring about nuclear reactions, and Cockcroft and Walton investigated one of these. Some of the details of their experiment are of interest and importance to us. They arranged to have a high voltage supply by which they could accelerate hydrogen ions drawn from a low pressure electric discharge in hydrogen; these ions were speeded up by a potential of about three quarters of a million volts, and they then fell on to a target of lithium. The resulting reaction, in which the more plentiful of the two lithium isotopes is involved, is described by the following equation:

$$Li_3^7 + H_1^1 = He_2^4 + He_2^4$$

From this one sees that the reaction yields two helium atoms, which, on account of the large amount of energy liberated in the reaction, have high velocities and so are simply artificial $\alpha$ particles. Each of the two helium atoms has a range in standard air of somewhat more than 8 cm., corresponding to a total energy liberation of about 17 MeV. Here is a reaction which yields much more energy than that supplied by the bombarding particle. Cockcroft and Walton had available protons with energies up to about 0.75 MeV but such energies are not essential to carry out this atomic transformation; it will work with protons with energies as low as 0.1 MeV, although it then occurs rather less frequently than when faster protons are employed. Unfortunately, in any case, it occurs far too rarely to be of practical use in the production of energy. When 0.2 MeV protons are used to bombard atoms of $Li^7$, only one disintegration occurs for every hundred million bombarding particles.

Let us return to the equation above and see how we can use it to determine the true mass of the lithium atom. We know from recent mass spectrograph measurements that the mass of the helium atom at rest is 4.0039 mass units and from the mass energy equation that 1 MeV is equivalent to $1.073 \times 10^{-3}$ mass units. Thus the mass equivalent of two helium atoms and an energy of 17 MeV is 8.0260 mass units, and this must be the mass equivalent of the bodies which, on interaction, give the two swift helium atoms. The mass of the hydrogen atom is 1.0081 and if we neglect the energy of the incident proton we conclude that the lithium atom* must have a mass of 7.0179. We have obtained this figure by taking mass spectrograph figures for the atomic masses of hydrogen and helium, and by assuming that all $Li^7$ atoms have

* Although the reactions are between nuclei, atomic and not nuclear masses are inserted in the equations.

the same mass and that in all transformations by protons of $Li^7$ to helium atoms an energy of 17 MeV is released. The mass obtained for the lithium atom—7.0179—can be compared with a mass spectrograph determination, and in this way a check can be made on the mass values given by the mass spectrograph and on the validity of our use of the mass energy equation. It is clear, however, that if mass energy equations are used to determine masses, it is possible to build up a table of atomic masses which depends on a few mass spectrograph determinations and on the study of many nuclear reactions. Proceeding in this way, it will often be possible to obtain several values for the precise mass of an atom of atomic number Z and mass number A; these values will be consistent only if the initial mass spectrograph values are correctly related to one another and if it is valid to use the mass energy equation as we did to determine the mass of $Li^7$. In fact this has been done; initial discrepancies were removed by a redetermination of the mass spectrograph value of the ratio $He^4$: $O^{16}$ and to-day there is a reliable table of atomic masses, some of which are most accurately known from measurements of the energy balance in nuclear transformations, and many of which have been determined only in this way. Thus the study of nuclear transformations has shown that the fullest information is to be obtained from nuclear reaction equations when the energy balance of the reaction as well as the reacting particles are shown in the equation. When this is done the nuclear reaction equation has on each side of it the same total nuclear charge or atomic number, the same total mass number, and the same total of mass and energy taken together.

These conclusions did not arise immediately from the work of Cockcroft and Walton; they initiated a line of investigation which was extended by them and by other experimenters who later possessed more powerful means of accelerating particles* than were available to Cockcroft and Walton in 1932, and it was from all these investigations that the validity of this use of the mass energy equation was verified.

(4) *Artificial radioactivity.*

It had long been appreciated that the radioactive elements were still found on earth because of the very long lives of the parent elements, thorium and uranium. It is quite possible that other radioactive elements were once present upon this planet, but they have disappeared because they had lives which were short compared with the period which has elapsed since their

* These include the cyclotron which was developed during the period under discussion and to which modern nuclear physics owes so much. Appendix I gives brief details of some methods of accelerating charged particles.

formation. Nevertheless, the possibility of producing artificial radioactive elements, that is radioactive forms of common elements, was not regarded seriously until the Joliots showed in 1933 that after the bombardment of aluminium by $\alpha$ particles there was present a short lived radioactivity with a half period of about 3 minutes.[5] It was possible to perform chemical tests to determine whether aluminium or some other element was responsible for this radioactivity; it was found to arise from phosphorus, a discovery which was in accord with the information available concerning its formation*, information which suggested that the material was $P_{15}^{30}$. Now this radio-phosphorus, as it was called, possessed the remarkable property of emitting positively charged particles which were identified as positrons. Its radio-activity caused it to be converted into $Si_{14}^{30}$, a stable isotope of silicon which is present to the extent of a few percent. in naturally occurring silicon; this is the isotope of silicon which results, on the instantaneous emission of a proton, when aluminium is bombarded by $\alpha$ particles, the reaction which was discovered and investigated in Rutherford's early disintegration experiments. Further investigation showed that $\alpha$ particle bombardment of other light elements gave rise to further artificial radioactive substances, many of them, like phosphorus, emitting positrons, and all of them having half lives which are reckoned in minutes. We shall discuss later the importance of these and other artificial radioactive elements but as they are not usually prepared by $\alpha$ particle bombardment, it seems appropriate to defer consideration of this matter.

* The reaction is $Al_{13}^{27}+He_2^4=P_{15}^{30}+n_0^1$; $n_0^1$ represents a neutron.

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## CHAPTER VIII

# NEUTRONS

(1) *Production of neutrons.*

The story of the discovery of the neutron is an interesting one, but in the present context it must be omitted in order to give space for consideration of the properties of neutrons. It must suffice to mention here that neutrons are produced when beryllium is bombarded by $\alpha$ particles of sufficient energy. Neutron sources are often provided by mixing beryllium powder with radium, in which circumstances the neutrons arise in the main from bombardment of the beryllium by the $\alpha$ particles emitted by the short lived products of radium. Neutrons may be produced in other ways, one of which is so important that it is mentioned here. If heavy hydrogen nuclei—deuterons—are given an energy of the order of $2 \times 10^5$ eV, as may be done by using relatively simple accelerating tubes, and if these deuterons are allowed to bombard stationary heavy hydrogen atoms in the form, for example, of heavy ice, a reaction takes place between pairs of deuterium nuclei. It appears that some collisions result in the release of neutrons, while others give two hydrogen atoms, one a radioactive substance with mass 3 and the other the common hydrogen isotope of mass 1. The neutron-yielding reaction is described by the following equation:

$$H_1^2 + H_1^2 = He_2^3 + n_0^1 + 3.2 \text{ MeV}.$$

This reaction, which is often referred to as the D on D reaction, is of interest because it results in the production of $He^3$; its main importance, however, lies in the fact that it produces neutrons which carry a considerable fraction of the energy balance of the reaction. By using high energy deuterons, which may be obtained from a cyclotron, neutrons of high energy may be produced.

As has already been mentioned, the neutron is a particle of mass number unity, and without charge. Apart from its lack of nuclear charge, it is very similar to a proton, and yet it is this lack of charge which makes it so different from any other particle.

(2) *Passage of neutrons through matter.*

The most remarkable property of a neutron is its ability to pass freely through matter which is impervious to any kind of atom. We can give a picture of the manner in which a neutron passes through matter by considering a

greatly magnified model of a piece of graphite sheet. Suppose that the sheet is 1 cm. thick and that it is magnified $10^{10}$ times. If we take our earlier estimates of nuclear dimensions, we see that a nucleus of $10^{-12}$ cm. diameter is magnified to be 0.1 mm. across; the electrons will be rather smaller than this. But what is more surprising is the very great distance between neighbouring nuclei. These were actually separated by about $2.3 \times 10^{-8}$ cm. and in our magnified model they will be 2.3 metres apart. Now a cube of graphite of 1 cm. side contains about $1.2 \times 10^{23}$ atoms. In the expanded model one face of this cube has an area of $10^{20}$ cm.$^2$ so that each cm.$^2$ of the model has behind it, in a depth of $10^{10}$ cm., 1200 atoms, each of which has a nuclear area of about $10^{-4}$ cm.$^2$ As the total area of the 1200 atoms is only 0.12 cm.$^2$ the area of the nuclei is about 12% of the area of the sheet containing them. Perhaps the electrons should also be included, for, although they are smaller than the nuclei, they are more numerous; but even if they are considered we find that the total area of all nuclei and electrons in this centimetre thick graphite sheet is probably less than half the area of the sheet. A sufficiently small particle will find many routes by which it can pass directly through such a piece of material; and the neutron is such a particle. Not all neutrons will avoid collisions as they attempt to pass right through a thin sheet of graphite or other material; but in many cases the collisions which occur are elastic collisions which result in little more than a change in the direction of motion of the neutron. Some of the neutrons which make such collisions will pass quickly through the material; others may have their directions reversed and some of these leave the material on the side on which they entered it. The result is that neutrons can escape fairly easily from a container made from a material which is experimentally found to be quite impervious to all gases. The rate of escape of neutrons will depend on a number of factors, one of which is the velocity of the neutrons. But if the nuclei have the sizes we have assumed, there is no way in which we can confine neutrons, for there is no material into which they cannot pass.

This discussion of the very tenuous nature of matter in bulk naturally raises a question. Why cannot protons or even hydrogen atoms move through matter just as easily as does a neutron? The case of the hydrogen atom is easily seen to be quite different from that of the neutron, for the hydrogen atom is a proton with an electron attached to it, and the diameter of the electron orbit is of similar dimensions to the distance between atoms in a solid. The hydrogen atom cannot move very far through a homogeneous material unless it leaves its electron behind it and then it is not a hydrogen atom.

Experimentally, even a proton does not go very far through solid matter,

and this for a very good reason. The neutron may find our estimates of atomic sizes fairly accurate, but the proton experiences nuclear fields at distances much in excess of $10^{-12}$ cm. from the centre of the nucleus. Thus to a proton the nuclei are much bigger than they appear to a neutron, and a "hole" through which a neutron can readily pass may not even exist for a proton. Not only is the transparency of a material different for a neutron and a proton; it differs enormously for protons of different speeds. The slower the proton goes, the fewer the places in which it can move, and the greater the chance that it will experience a change of direction, and a loss of energy, in its passage through the electric field of a nucleus.

Although the picture just given does not describe all the features of the motion of neutrons through matter, it does serve to show why materials which are impervious to hydrogen atoms or fast ions can be readily traversed by neutrons. The crucial difference is the absence of charge on the neutron, and for this reason the neutron has many fewer interactions with matter than a proton for example. It is partly for this reason also that radioactivity was studied for over thirty years before the neutron was discovered.

Let us consider in more detail what happens to a neutron which moves into a thin sheet of material. There are several possibilities, one of them being that the neutron takes a path that allows it to pass straight through. But not all possible paths will avoid the nuclei of the atoms in the sheet, and some neutrons will make collisions; whenever there is a collision there are two consequences: the neutron loses some of its energy and also changes the direction of its path.

(3) *Energy lost by a neutron in an elastic collision.*

Let us first examine the circumstances which determine the amount of energy transferred by a neutron to a struck nucleus as a result of a collision. The energy transferred will depend on the path and energy of the neutron and on the mass of the struck nucleus. The collision, if it is elastic, as we shall suppose, will be such that the energy and momentum of the neutron before the collision will equal the total energy and momentum, respectively, of the neutron and the nucleus after the collision. These requirements enable us to determine the nature of the collision between a neutron and a nucleus of given mass in which there is the maximum transfer of energy from the neutron to the struck nucleus; we find, as we might expect, that this occurs with a head-on collision. For this simple type of collision we can readily determine what happens and easily calculate the energy transferred. For if m is the mass of the neutron, u its initial velocity, and v its final velocity, we have from the conservation of energy the following relation:

$$\tfrac{1}{2}mu^2 = \tfrac{1}{2}mv^2 + \tfrac{1}{2}MV^2.$$

Here M is the mass of the struck nucleus and V its final velocity. Again, from the condition that momentum is conserved we also have:

$$mu = mv + MV.$$

If we eliminate v from these equations and calculate the kinetic energy of the struck nucleus, i.e., $\frac{1}{2}MV^2$, we find that it is equal to

$$\frac{1}{2}mu^2 \frac{4Mm}{(M+m)^2}$$

This is the energy transferred by the neutron to the struck nucleus. Now if M is equal to m, as would be the case if the collision was between a neutron and a hydrogen nucleus, the energy transfer amounts to $\frac{1}{2}mu^2$, i.e., the neutron gives up all its energy to the hydrogen nucleus; this type of collision is illustrated in Fig. 18. Of course not all collisions between a neutron and a hydrogen nucleus are head-on collisions, but some few are, and in these the neutron gives all its energy to the struck nucleus; in other close collisions between a neutron and a hydrogen nucleus, the neutron transfers appreciable amounts of its energy to the nucleus, but not the whole of it. Thus when a neutron moves through material containing hydrogen it occasionally makes collisions with hydrogen nuclei and as a result it loses energy, the amount of energy lost depending upon the nature of the collision. If the neutron is a fast one, it is sufficiently accurate to imagine that the hydrogen nucleus is at rest, and in this case the colliding neutron loses a fraction of its energy which can be quite simply stated in terms of the angle through which the collision deflects it. In the case of slower neutrons it may be necessary to consider the finite velocity of motion of the hydrogen atom; this is certainly the case with neutrons having energies close to the mean kinetic energy of thermal agitation of a gas molecule at the temperature of the matter through which the neutron moves. Such neutrons are known as thermal neutrons. At any given collision between a thermal neutron and a hydrogen nucleus there may be either gain or loss of energy, for when the neutrons have the same average kinetic energy as is possessed by the molecules amongst which they move, on balance they neither gain nor lose energy. Individually, however, neutrons regularly gain and lose energy as a result of collisions, and consequently, amongst thermal neutrons, there will be a considerable

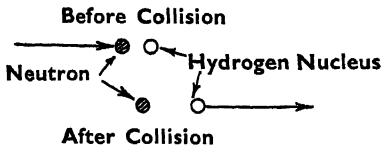



**Fig. 18.** Head-on collision between neutron and $H^1$ nucleus. The lengths of the arrows represent the speeds of the particles.

range of neutron energies, just as there is a range of energies of the molecules of a gas. Thus the neutrons which pass through hydrogenous material suffer a loss of energy consequent upon collisions with hydrogen nuclei; this loss of energy continues until the neutrons are reduced to thermal energies in which circumstances they remain in temperature equilibrium with the matter within which they move.

Contrast what happens when a neutron makes a collision with a nucleus of a heavy atom, and let us consider as the simplest case a head-on collision; in this case, as our formula shows, the struck nucleus has transferred to it only a small fraction of the initial energy of the neutron. The directions of motion before and after the collision are the same as those in Fig. 19. A neutron passing through a lead plate may make collisions with lead nuclei with consequent changes in the direction of motion, but as it transfers only 2% of its kinetic energy on a head-on collision with a lead nucleus, it will not lose its energy by elastic collisions at a rate which is in any way comparable with that achieved when it passes through a material, such as water or paraffin wax, in which hydrogen is one of the main constituents.

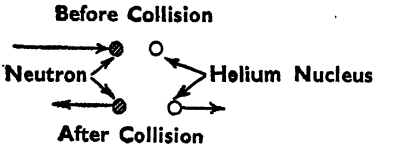



**Fig. 19.** Head-on collision between a neutron and a $He^4$ nucleus. The lengths of the arrows represent the speeds of the particles.

We shall see shortly that means for slowing down neutrons are of importance in some methods for releasing atomic power. In view of the needs of subsequent chapters, it is appropriate to determine here the energy transfer when a neutron makes a head-on collision with a deuterium nucleus or with a carbon nucleus. In the first case 8/9 of the neutron energy is transferred to the deuterium atom, but in the second case only about 2/7 of the neutron energy is passed to the carbon atom. It appears, then, from these figures, that heavy hydrogen—deuterium—is almost as effective as hydrogen of mass number unity in slowing down neutrons, but that carbon, and of course slightly heavier elements, are markedly less efficient; the really heavy atoms are relatively useless for this purpose.

(4) *Neutron scattering.*

In order to put the matter of neutron scattering on a quantitative basis, we require to know the likelihood that a neutron makes an elastic collision when passing through a piece of material of known composition. Let us imagine a narrow parallel beam of neutrons, in the path of which is placed a thin

sheet of scattering material. If this sheet is thin enough, only a few neutrons will make nuclear collisions which are close enough to deflect them appreciably and of these few neutrons an entirely negligible number will make two nuclear collisions. In these circumstances a measurement is made of the number of neutrons scattered out of the beam. By using different thicknesses of the scattering material it may be shown that the number of neutrons scattered is proportional to the thickness of the scatterer, as long as this thickness is not too great; or in other words that the number of neutrons scattered is proportional to the number of atoms per cm.$^2$ of the scattering material. As we know the absolute masses of atoms we can readily calculate the number of atoms in a cm.$^3$ of material and then the number of atoms per cm.$^2$ in a sheet of the material of thickness t, and finally the scattering effect per atom. If, for example, we consider a piece of paraffin wax of density 0.9 g. per cm.$^3$ and suppose that it contains two hydrogen atoms for every carbon atom, we see that 14 g. of wax will contain 1 g. atom of carbon and 2 g. atoms of hydrogen. Now in 1 g. atom there are about $6 \times 10^{23}$ atoms, so that in 7 g. of paraffin wax there are $6 \times 10^{23}$ hydrogen atoms and in 1 cm.$^3$ about $8 \times 10^{22}$ hydrogen atoms. If we find that the hydrogens in a piece of wax 1 mm. thick scatter 9% of the neutrons in the beam, we can say that all the hydrogen atoms in the piece of wax produce a target for neutrons which has an area of 9% of that of the piece of wax; the hydrogen atoms in each cm.$^3$ of wax thus present an area of 0.09 cm.$^2$, and each atom provides a target of $12 \times 10^{-24}$ cm.$^2$ This area is called the scattering cross section of the hydrogen atom for the neutrons in the beam. The use of the idea of scattering cross section is universal in the discussion of the behaviour of neutrons passing through matter, and it is for this reason that it has been discussed in some detail. It will be noticed that the figure given above, which is derived from experiments on the passage of neutrons through paraffin wax, is appreciably larger than might have been anticipated from our earlier estimates of nuclear sizes. If we looked at the matter from the point of view of the collision of two elastic spheres, we would assume that these scattering experiments gave cross sections which depended on the size of the neutron as well as on the size of the hydrogen nucleus, and in part, perhaps, this contributes to the high value obtained. But when experiments are made in different circumstances, it becomes clear that no precise figure can be given for the size of the hydrogen nucleus. It is sufficiently encouraging to find that estimates of nuclear size derived from $\alpha$ particle and neutrons scattering experiments are sometimes of the same order of magnitude.

The figure given for the neutron scattering cross section of hydrogen, viz. $12 \times 10^{-24}$ cm.$^2$, has not much significance for anyone who does not deal frequently with the processes of neutron interaction with matter, and for this reason

it is desirable to give the relationship between this cross section and the average distance the neutron will move between collisions with hydrogen atoms. It is easily shown that this distance, which we will call the mean free path for neutron collision, is inversely proportional to the collision cross section and to the number of nuclei available for collision in 1 cm.$^3$ of material. The exact relationship is given by the equation:

$$\text{Collision cross section} \times \text{number of nuclei per cm.}^3 = \frac{1}{\text{mean free path.}}$$

For the case of a paraffin wax in which there are $8 \times 10^{22}$ hydrogen atoms per cm.$^3$, each with a collision cross section of $12 \times 10^{-24}$ cm.$^2$, the mean free path will be nearly 1 cm. This may suggest that neutrons do not pass very readily through paraffin wax, but it will be realized that even a mean free path of 1 cm. is very large compared with the range of an $\alpha$ particle or of a proton in solid matter.

(5) *Detection of neutrons.*

We have discussed for some time the passage of neutrons through matter, but nothing has been said concerning the way in which neutrons are detected. It will be realized that neutrons pass easily through matter because of their infrequent interactions with atoms; for this reason they are difficult to detect. The simplest way of showing the presence of fast neutrons is to pass them into an expansion chamber which is filled with hydrogen. Some neutrons will make close collisions with hydrogen nuclei and as a consequence considerable amounts of energy will be transferred to the struck nuclei, which will then be able to form tracks in the chamber; these energetic hydrogen nuclei are conveniently called " knock-on hydrogens " or " knock-on protons." Occasionally, when there is a head-on collision, the neutron will transfer all its energy to the hydrogen nucleus, and in such cases the direction of the track of the knock-on proton will be the initial direction of the neutron, and from the length of the track the energy transferred to the hydrogen nucleus may be estimated; this energy is the initial energy of the neutron. If the neutrons come from a source of small dimensions, their directions in the cloud chamber are determined, and neutron energies can be estimated in the case of collisions in which only a portion of the energy of the neutron is transferred to the struck hydrogen nucleus. In such collisions, one of which is illustrated in Fig. 20, the direction of the proton track does not correspond with that of the motion of the neutron either before or after the collision, but the energy transferred to the knock-on hydrogen depends on the initial energy of the neutron and on the angle between the initial neutron path and that of the knock-on hydrogen. Fig. 21 shows an expansion

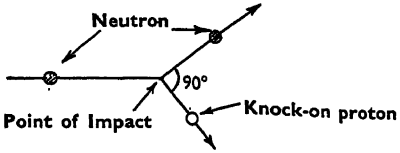



**Fig. 20.** Collision between a fast neutron and a hydrogen nucleus. The lengths of the arrows represent the speeds of the particles.


**Fig. 21.** Wilson Cloud Chamber photograph showing tracks of knock-on protons. The source of neutrons was at S and gave 2.4 MeV neutrons from the D on D reaction.
(From *The Newer Alchemy*, Rutherford, Cambridge University Press.)

chamber photograph of the tracks of hydrogens knocked-on by neutrons. Although this method of observation is in some ways satisfactory, it is far from sensitive. As we saw above, some neutrons have a mean free path in paraffin wax, where there are $8 \times 10^{22}$ atoms per cm.$^3$, of about 1 cm.; these neutrons will have, in hydrogen at atmospheric pressure, where there are only $5 \times 10^{19}$ hydrogen nuclei per cm.$^3$, a mean free path of about 16 metres. This arithmetic shows that only a few of the neutrons passing through an expansion chamber of moderate size will yield the knock-on proton tracks which alone reveal their presence. It is to be remembered, also, that although the method gives information about neutron energies, it is only suitable for neutrons with energies in excess of a few tens of thousands of electron volts, for which neutrons the collision cross section is even smaller than the value assumed in the calculation above.

(6) *Neutron capture processes.*

There are other ways of detecting the presence of neutrons, some of them much more sensitive than the expansion chamber method already discussed, but before these are described, it is desirable to make some further examination of the phenomena occurring when neutrons pass through matter. For clarity of discussion we will assume that means are available to enable us to measure the energy of neutrons. For neutrons with energies of the order of 1 MeV, paraffin wax is more transparent than for the slower neutrons we have been discussing in our example above; at this high energy the scattering cross section of a hydrogen atom is little more than $10^{-24}$ cm.$^2$, giving a mean free path in paraffin wax of about 10 cm. For neutrons with less energy, the mean free path in paraffin wax is shorter than 10 cm.; neutrons with an energy of 1 eV have a mean free path of approximately 1 cm., and neutrons with an energy of about 1/30 eV—the same energy as the kinetic energy of an atom in a gas at room temperature—travel about 0.3 cm. between collisions. For still slower neutrons, the mean free path will be even smaller than this. It appears then that the mean free path of neutrons in paraffin wax is a quantity which depends on the velocity of the neutrons, and that for neutrons with low energies it is about 1/30 of its value for high energy neutrons. Now for neutrons with energies of about 1/30 eV—these are called thermal neutrons because, as has just been mentioned, they have the same energy as the thermal energies of gas molecules at room temperature—not only does elastic scattering occur between neutrons and hydrogen nuclei; some of the neutrons are actually captured by the hydrogen nuclei. We again introduce the idea of the cross section of the nucleus, but this time we call it the capture cross section. For thermal neutrons the capture cross section of the hydrogen nucleus is very small, and amounts to about $0.4 \times 10^{-24}$ cm.$^2$, a

cross section which would give a neutron a mean total path of about 30 cm. in paraffin wax. This figure refers to thermal neutrons which have a mean free path of about 3 mm. in paraffin; on the average, then, these thermal neutrons make about one hundred collisions with hydrogen nuclei before capture takes place. For faster neutrons hydrogen has a still smaller capture cross section, and in fact any neutron entering a hydrogenous material such as paraffin wax will almost certainly be slowed down to thermal energies before it is captured by a hydrogen nucleus; but eventual capture is certain unless of course the neutron leaves the hydrogenous material. Even after the neutron has been reduced to thermal energies, it has the prospect of a path of 30 cm. in paraffin wax; but as its velocity is then about $2 \times 10^3$ metres a sec. its life time in paraffin wax is only of the order of $10^{-4}$ sec. What if it does escape? It may make a close collision with some nucleus by which it is captured, or alternatively, it is believed, it may convert itself into a proton and an electron. In view of the difficulty of confining neutrons this possibility is an awkward one to verify; but the neutron has sufficient mass to make this process possible from the point of view of the mass energy equation, and there are good reasons for believing that this transition may actually occur. It can only be important, however, when alternative possibilities of capture are exceedingly small, and in most cases it need not be considered.

The passage of a neutron through matter involves a number of processes which may be summarized as follows. In the first place the nuclei are spaced at great distances compared with their own dimensions, and through the holes between them the neutrons are able to pass freely because they are unaffected by the strong electric fields existing between the nuclei. Nevertheless, occasionally the neutrons make collisions with nuclei and either the neutron is captured by the nucleus or else it rebounds after an elastic collision in which some of the energy of the neutron is transferred to the nucleus and the direction of motion of the neutron is altered. The relative importance of the two processes, and indeed the probability of hitting or missing a given nucleus, depends on the velocity or kinetic energy of the neutron. Numerically the various possibilities are expressed by stating the elastic collision and capture cross sections of a given nucleus for neutrons of a given energy.

It is a matter of interest and importance to consider how the capture cross section of a nucleus may be expected to vary with neutron velocity. The simplest case, of which the capture of slow neutrons by hydrogen is an example, involves a capture cross section which is large only at low neutron velocities. The cross section is inversely proportional to the neutron velocity, or put in other words it is proportional to the length of time for which the neutron

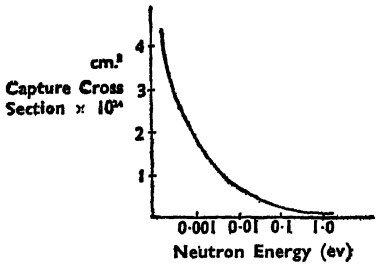



**Fig. 22.** Relation between capture cross section and neutron energy. (No resonance levels.)

remains in the immediate vicinity of the capturing nucleus. Fig. 22 shows the variation of capture cross section to be expected in such a case.

Usually, however, neutron capture cross sections show a much more complicated variation with neutron velocity, and in particular there are frequently certain neutron velocities for which the neutron capture cross section is very high. The capture process then occurring has some similarity to resonance phenomena which are found in physics in connection with electrical and mechanical oscillations, and for this reason it is known as resonance capture. In electrical resonance, for instance, a circuit gives large oscillations for an applied voltage of one particular frequency. In the case of resonance neutron capture, the neutron is readily captured because it has the correct energy. Upon neutron capture the nucleus generally has more energy than it can retain for any appreciable length of time; in terms of the description usually given the nucleus is "excited," and it proceeds immediately to dispose of the "excitation energy" so as to reach an equilibrium state in which it can remain. When resonance capture takes place, the energy transferred to the nucleus by the captured neutron is such as to make it fit readily into the structure of the new nucleus arising from its absorption, a state of affairs which is usually described by saying that the energy of the neutron corresponds to that of a particular resonance capture level. For a given nucleus there may be many of these resonance neutron capture levels, but they give rise to large neutron capture cross sections only where they occur at neutron energies close to the thermal region, for it is only then that the neutron passes a nucleus sufficiently slowly to give rise to a high chance of capture.

In some cases resonance capture cross sections are large and in others they are small; some levels are broad and others narrow. In the region of low neutron energies, heavy elements have neutron capture resonance levels which are irregularly spaced at distances of about 10 eV. For light elements the resonances are much broader and although they are more widely spaced than for heavy elements they sometimes overlap. This overlapping also occurs in the general case of the capture of neutrons of higher energy; here no discrete resonances are found and the capture cross section falls with increasing velocity, at first inversely as the velocity, but at energies of the

order of 1 MeV the capture cross section decreases inversely as the energy.

A representative neutron capture cross section curve for slow neutrons is shown in Fig. 23, where it is supposed that only one resonance level exists. The position of the resonance level is taken as the neutron energy at which the capture cross section is maximum; the width of the level is the range of neutron energy for which the capture cross section is greater than half the resonance value. In the diagram of Fig. 23 the resonance level is at 2 eV and

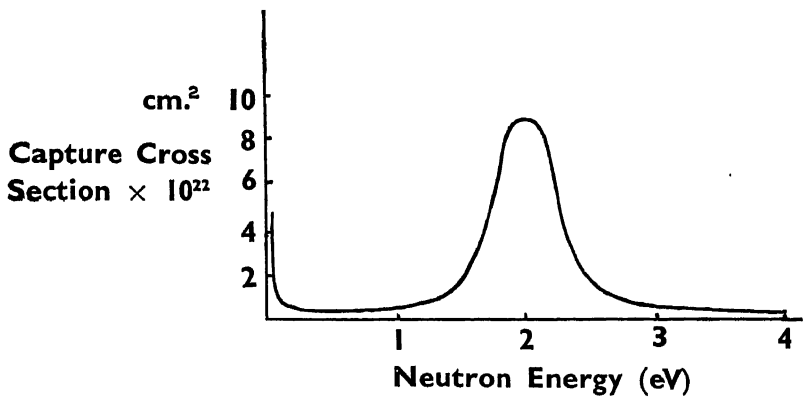



**Fig. 23.** Relation between capture cross section and neutron energy. (One resonance level.)

it has a width of 0.5 eV. This value is a reasonable one for a heavy capturing nucleus.

It should be realized that the overall shape of a neutron capture cross section curve is determined by two factors, one of which is the situation and nature of the resonance capture levels. It is sometimes useful to think of this as the only factor involved and then, to obtain a true picture of the variation of capture cross section with neutron velocity, to take account of the fact that the capture cross section is also inversely proportional to the neutron velocity. In this way we obtain a clear picture of the reasons for observed variations of capture cross section. In the neighbourhood of a sharp resonance capture level, the shape of the curve depends almost entirely on the nature of the resonance level; at considerable distances from resonance capture levels the effect of the time spent by the neutron in the vicinity of a capturing nucleus is of much greater importance, and the curve shows that the cross section is inversely proportional to the neutron velocity.

There are two cases in which the capture cross section of a material is inversely proportional to the velocity of the neutrons. The first is that just discussed; it arises when the resonance energy of the lowest level is some considerable distance above thermal energies, and when the resonance level is sharp. Then, for neutron energies up to about one tenth of the resonance value, the capture cross section is inversely proportional to the neutron velocity. The other case is that in which the width of the resonance level is great. If, for example, a resonance level situated at 10 eV has a width of 100 eV, the resonance capture curve itself* will give rise to very small changes of cross section in the region from 0 to perhaps 25 eV; when account is taken of the effects of increasing neutron velocity, it is seen that for neutron energies up to 25 eV the capture cross section varies inversely as the velocity. Boron and lithium both have very wide resonance capture levels, and for slow neutrons both show a capture cross section that is inversely proportional to the velocity of the neutron.

(7) *Neutron reactions.*

Let us now discuss the consequences of neutron capture. As should be quite clear, the capture of a neutron does not alter the chemical nature of the atom by which it is captured. To take the simplest example, consider the capture of a thermal neutron by a hydrogen atom. The result is the formation of a heavy hydrogen atom. As the sum of the masses of the hydrogen atom and the neutron is somewhat in excess of that of a heavy hydrogen atom, the nucleus resulting from neutron capture has excess energy which it liberates by emitting radiation in the form of $\gamma$ rays. This reaction is written

$$H_1^1 + n_0^1 = H_1^2 + 2.17 \text{ MeV}.$$

In view of the fact that radiation is emitted after the capture of the neutron, this process is commonly referred to as radiative capture.

Now this is a particularly simple case of neutron capture, but because of its simplicity it is worthy of further consideration. As might be suspected the reaction is reversible; if high energy $\gamma$ rays are sent through heavy hydrogen, some of the $\gamma$ rays are absorbed; their energy is given to a deuterium nucleus which may then split into a proton and a neutron, of which the kinetic energy will depend upon the amount by which the energy of the $\gamma$ ray used exceeded 2.17 MeV, the energy of the $\gamma$ ray emitted on the capture of a neutron by a hydrogen atom. The process by which heavy hydrogen is disintegrated by $\gamma$ rays is known as photo-disintegration.

* Momentarily we are overlooking the effects arising from the time spent by the neutron in the neighbourhood of the nucleus by which it may be captured.

In general, however, we do not find that a stable nucleus is formed as a result of neutron capture. The new nucleus may immediately split up, or alternatively it may be a radioactive atom which disintegrates within a short or longer time after its formation; it is found, too, that neutron capture is not invariably followed by the same reaction. We have already met alternative reactions in the case of heavy hydrogen bombardment of heavy hydrogen—D on D—and in connection with $\alpha$ particle bombardment of aluminium, where there are sometimes protons emitted and on other occasions the formation of radio-phosphorus. In a similar way, on neutron capture, a nitrogen nucleus may give a carbon nucleus and a proton or alternatively a beryllium nucleus and an $\alpha$ particle. Consequently there is a very large number of reactions resulting from neutron capture, and there is no advantage in mentioning many of these. It seems desirable, however, to discuss some typical cases and to mention some reactions which are of use in the detection of neutrons. This chapter will give no discussion of nuclear fission, for although this is one of the consequences of neutron capture it is a process of such importance and interest to us that a separate chapter is devoted to it.

The simplest neutron reaction, radiative capture, is represented by the capture of neutrons by hydrogen. The neutron capture gives an isotope of the capturing nucleus; this isotope has a mass number one greater than the nucleus from which it was derived. In general this isotope is formed in a condition in which it possesses more than its normal energy; the surplus energy is radiated as a $\gamma$ ray.

There are a great number of reactions of this type, and of these the cases of cadmium, silver, indium and rhodium are worthy of mention. Cadmium is of interest because it has a very large capture cross section for thermal neutrons; the resulting cadmium isotope appears to be stable. Silver, indium and rhodium, which exhibit resonance capture of the type discussed above, all show considerable capture cross sections for neutrons which have slightly greater energies than those possessed by thermal neutrons, and all give rise to short-lived artificial radioactive elements which emit $\beta$ particles.* Since a Geiger-Müller tube responds to single $\beta$ particles, these radioactive substances form convenient indirect detectors of neutrons of the appropriate energy.

As has already been mentioned, neutron capture by a nitrogen nucleus is sometimes followed by the immediate emission of a proton. A similar reaction occurs with a number of other elements, especially light ones. The

* The eventual radioactive transformation of these nuclei occurs long after the neutron capture process; it is not believed that radiative capture in the case of cadmium is essentially different from that occurring when, for example, silver captures neutrons.

new element resulting from this reaction has the same mass number as the element which captured the neutron, but there is a decrease of unity in atomic number. In some cases the product nucleus is radioactive. The reaction for nitrogen may be taken as typical. For it we have

$$N_7^{14} + n_0^1 = C_6^{14} + H_1^1$$

From the point of view of this book a reaction of this type is not important.

The last type of reaction to be considered is a rather rare one. It is the case of neutron capture resulting in the immediate emission of an $\alpha$ particle, a type of reaction which sometimes occurs as an alternative to that described above when a nitrogen nucleus captures a neutron. Two important reactions of this type are those occurring on neutron capture by lithium or by boron. The reactions are

$$Li_3^6 + n_0^1 = He_2^4 + H_1^3$$

and

$$B_5^{10} + n_0^1 = He_2^4 + Li_3^7$$

In both cases the capture cross section for slow neutrons is reasonably large, especially in the case of boron, and in both cases appreciable energy is liberated as a result of the reaction, so that the particles released are capable of forming a considerable number of ions.

Both these reactions are of importance because they provide satisfactory means for detecting neutrons. The methods previously mentioned—the examination of knock-on protons arising from neutron impacts, and the use of artificial radioactive substances formed on neutron bombardment—are subject to serious limitations. The use of knock-on protons is of great historical importance, and it is still of use for the detection of high energy neutrons, especially as the method can be used to measure the energy of the neutrons. Again, silver is a satisfactory detector for neutrons just above the thermal range of energy, but it is unsuitable for thermal neutrons and in any case it is not very sensitive. On the other hand thermal neutrons are captured by both lithium and boron, and on capture they give rise to the emission of swift helium atoms which give sufficient ionization to make them easily detected. In a slow neutron detector use is made of an ionization chamber connected to a linear amplifier and counter. The inside of the ionization chamber is lined with a boron or lithium compound or alternatively the chamber is filled with boron trifluoride; when a thermal neutron passes into the chamber, it has a reasonable probability of capture by the boron or the lithium, and if this happens there is high probability that the resulting fast particles will produce ionization in the chamber and a large pulse at the output of the amplifier. In this way satisfactory neutron-sensitive chambers have been constructed, and these have been invaluable in making measure-

ments of neutron intensities and in measuring scattering and capture cross sections of different elements.

A few remarks should be made concerning the methods used for measuring the energy of neutrons, particularly of the slower neutrons. At first sight this looks a difficult problem and so it has proved to be. In the case of fast neutrons we have already seen that their energies may be determined from the ranges of knock-on hydrogens with which they have made head-on collisions. In some cases the energy of slow neutrons can be determined directly. Where neutrons are emitted from a source as a result of bombardment by particles accelerated by a high voltage, it is often possible to arrange that the high voltage is applied periodically for short intervals of time. By this means the neutron source is made to yield a series of short bursts of neutrons, and by measuring the time taken for these neutrons to travel from the source to a distant detector, the velocity of the neutrons may be determined. Alternatively, bursts of neutrons may be obtained by mechanical means; when thermal neutrons are being investigated, cadmium shutters, built into a rotating disk, are used to cause a periodic interruption of the neutrons so as to make possible a direct measurement of their velocity.

Many of the determinations of neutron energies, however, make use of the known variation of boron or lithium neutron capture cross sections with neutron velocity. If a beam of neutrons is passed through an absorbing screen containing boron, neutron capture will occur, but as this occurs more frequently for slow neutrons than for fast ones, the beam is made relatively poorer in slow neutrons. The extent to which boron absorbs the neutrons responsible for some particular resonance capture process is then an indication of the velocity of these neutrons. If for example the capture cross section of boron for thermal neutrons is ten times as large as that for the neutrons that are captured by silver to form radioactive silver, we deduce that the latter neutrons have ten times the speed and one hundred times the energy of thermal neutrons or in other words an energy of about 3 eV.

By the use of such principles, determinations have been made of the neutron energies at which various resonance capture processes occur, and consequently at the present time there is not a great deal of difficulty in determining the energy range of the neutrons in a neutron beam. It should be borne in mind that a beam of neutrons is not like a beam of charged particles; it is difficult to arrange that it is well defined in width and to ensure that all the neutrons in the beam have the same energy; in many ways a beam of neutrons more closely resembles a beam of neutral molecules than it does a beam of protons or electrons. Fortunately, however, we now know enough about neutrons to make it easy to detect them, and in fact the methods

of detection of neutrons compare favourably in sensitivity with those used for detecting charged particles.

In 1932, when the neutron was discovered, the task of finding out much about it must have appeared very difficult or hopeless; as things have turned out, some properties of neutrons are very favourable for the investigation of the neutron and of the reactions in which it takes part, and to-day there is an immense amount of detailed information concerning it. This information, and the experimental methods used to obtain it, were of the utmost assistance in the nuclear studies that led to the realization of atomic energy and the atomic bomb.

In the following there is some information concerning the properties of neutrons: " Why Smash Atoms ? ", A. K. Solomon, (Pelican Books, A 141); " The Newer Alchemy ", Rutherford, (Cambridge University Press); " Elements of Nuclear Physics ", F. Rasetti, (Blackie and Son, Ltd.)

## CHAPTER IX

# NUCLEAR FISSION

(1) *The bombardment of uranium by neutrons.*

Amongst the substances which were early subjected to bombardment by neutrons were the heavy radioactive elements, uranium, protoactinium and thorium. These are $\alpha$ particle emitting elements of rather long life, and they occupy, in the order given, the three highest places in the periodic table. Particular interest was attached to the case of uranium, for if this behaved as did so many other elements it would capture neutrons and from $U^{238}$ would be obtained $U^{239}$, a substance of higher atomic weight than any other known to occur naturally upon the earth. There was no reason to assume that $U^{239}$ would emit $\alpha$ particles as do uranium I and II and actino-uranium ($U^{238}$, $U^{234}$ and $U^{235}$); $U^{239}$ might behave as do so many other nuclei after neutron capture, and emit $\beta$ particles, giving rise in this case to a new element of mass number 239 and atomic number 93.

Investigation showed that bombardment of uranium by neutrons did indeed produce radioactivity in which $\beta$ particles were emitted; presumably new elements were being formed—elements with higher atomic numbers than 92. After chemical treatment of uranium which had been subjected to bombardment by neutrons, it was found possible to isolate substances which showed $\beta$ radioactivity and which were chemically different from uranium; in addition it appeared that there was some $\beta$ ray activity from an element which was chemically identical with uranium. To clarify the position it was desirable to establish the identity of these new radioactive elements. If they were elements of atomic number higher than that of uranium, their precise chemical properties would be unknown, in which case these properties could be predicted only by making use of the periodic table after first assuming a value for the atomic number of the unknown element being investigated. Reference to the periodic table shows that a substance of atomic number 93 may have properties similar to those of manganese, masurium or rhenium; it probably would precipitate with one or other of these elements. If we mix our unknown substance with manganese, and we find on precipitating the manganese that the unknown is not brought down with the precipitate we will be suspicious of our assumption that it is of atomic number 93; but as it happens that many different elements precipitate with certain manganese compounds, a positive result is encouraging but it is not in the least conclusive. Further tests are needed.

If the new elements were not of atomic number 93 or higher, they might be of atomic number 90 or 91; it was hardly likely that they would be still lower than this. And experiment soon showed that they were not identical with any element between uranium and mercury. There appeared to be no doubt; the elements in question must have atomic numbers greater than 92. These elements were called the trans-uranic elements, and they were the subject of extended researches.

Information soon obtained showed that there appeared to be a large number of trans-uranic elements formed by the successive emission of β particles. The problem was to ascertain the nature of these elements and to determine the transformation constants of the radioactive decay exhibited by them. Although this problem appeared straightforward, it proved to be unexpectedly difficult of solution; there were so many of these short-lived radioactive substances. Not only were there a great many trans-uranic elements; many of these, though chemically identical, appeared in a number of alternative nuclear forms, each of which had its own period of radioactive decay. These alternative forms were of course isotopes, but they were more than this, for on any reasonable view of their mode of formation they had identical mass numbers as well. The existence of radioactive isotopes with identical mass numbers and different radioactive transformation constants is so rare that the discovery of examples of this type of isomerism amongst the trans-uranic elements made it appear that their radioactivity was different from anything previously known.

In endeavours to ascertain the atomic numbers of these trans-uranic elements, many chemical experiments were made, and of these two are of particular interest to us. The Curie-Joliots found that if a compound of the rare earth lanthanum was added to uranium which had been subjected to neutron bombardment, one of the resulting radioactive substances could be precipitated with the lanthanum. They were struck with the great similarity between the chemical properties of this radioactive substance and those of lanthanum, but as they believed that the two substances were not identical, they assumed, for reasons which are apparent on examining the atomic table, that they were dealing with an isotope of actinium. In a similar way, they discovered that if barium replaced lanthanum some of the trans-uranic radioactive substances could be precipitated with barium. As is well known from the work of Madame Curie, barium and radium are chemically similar, so much so, indeed, that they are quite difficult to separate. It was natural then, to suppose that the radioactive substance which precipitated with barium was a new form of radium. But this conclusion, and similarly the belief that at least one of the radioactive substances was actinium, involved serious

difficulties. It was not very satisfactory to be faced, a short time later, with the necessity of recognizing the existence of four new short-lived types of radium. But even more difficult was the problem of explaining how radium of atomic number 88 was formed from uranium of atomic number 92; this would require the immediate emission of two $\alpha$ particles, an unlikely consequence of the capture of a neutron by a heavy atom. And there was no evidence at all that neutron bombardment of uranium led to the emission of any $\alpha$ particles.

This difficulty was finally overcome when Hahn and Strassmann[1] investigated the properties of the new short-lived radium that was precipitated with barium. For they found, to their astonishment, that the so-called radium did not behave as expected, for even when Madame Curie's methods were used, the new radioactive substances could not be separated from barium. Only one conclusion was possible; the short-lived radium was not radium at all; it was barium! And just as certainly, the actinium which the Joliots precipitated with lanthanum was not actinium but was lanthanum itself.

Immediately upon the publication of Hahn and Strassmann's paper, Frisch[1] suggested that neutron bombardment of uranium caused it to split into two massive fragments, one of which was a radioactive barium. He called the process uranium fission, and he estimated that the fission fragments should possess a total kinetic energy of the order of 200 MeV. Particles emitted with an energy of 100 MeV must give rise to very large amounts of ionization, of the order of ten times that produced by the fast $\alpha$ particles from ThC′. An ionization chamber and linear amplifier should easily provide conclusive evidence of intense bursts of ionization of this type. And so it proved. Frisch, at that time in Denmark, physicists in many parts of the U.S.A., the Joliots in Paris and workers in England quickly carried out experiments which showed without doubt that neutron bombardment of uranium did give rise to bursts of ionization which were about twenty times as large as those produced by the normal uranium $\alpha$ particles. Fig. 24 gives an example of the records obtained in an experiment of the type described. Later on, as a result of more precise electrical measurements of the ionization produced by the products of fission, it was found that each fission fragment had a kinetic energy of about 100 MeV, just as was expected. But even the earliest tests confirmed the views that Frisch first put forward to explain the presence of barium in a sample of uranium that had been bombarded by neutrons.

The fission process gives fragments which are capable of forming easily visible tracks in the expansion chamber, and not long after the discovery of fission, photographs were published in which the tracks of the fission fragments could be seen. These tracks are rather short—about 3 cm. in standard

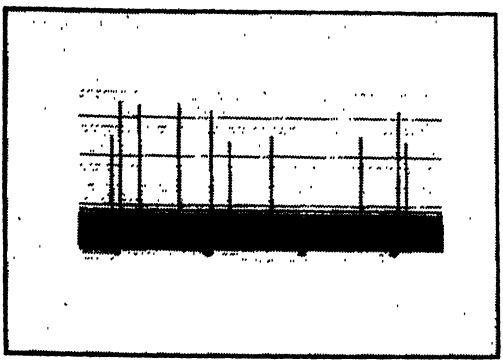


**Fig. 24.** Oscillograph record of ionization caused by fission fragments from uranium. The length of each long black line is proportional to the ionization from a single fission fragment. The $\alpha$ particles from uranium I do not give sufficient ionization to show on this record.

(From the *Journal of Applied Physics*, Vol. II, p. 5 (1940).

air—and in one respect they are different in appearance from an $\alpha$ particle track. The heavy fission fragments make frequent close encounters with the nuclei of lighter atoms to which they communicate appreciable amounts of energy. In consequence, the tracks themselves show occasional spurs, which arise from those encounters resulting in a sufficient transfer of energy to enable the struck atom to ionize. On account of the high mass of the colliding fission fragment, its direction of motion is relatively little affected by such encounters. Figs. 25 and 26 illustrate the appearance of fission fragment tracks in the expansion chamber.

This process of nuclear fission is quite different from any other nuclear or atomic process previously known. In other nuclear reactions, protons, neutrons, and even $\alpha$ particles are ejected from atoms when they are subjected to suitable bombardment, but no heavier particle than the helium nucleus had ever been found to be emitted in a nuclear disintegration. In the case of uranium fission, bombardment of uranium by neutrons sometimes brings about such instability that the uranium nucleus splits into two nearly equal portions. As these fragments of the uranium nucleus both carry many positive charges, they repel strongly as soon as they have become separated from one another. Even when the centres of the fragment nuclei are within $10^{-11}$ cm., and this represents a separation of the order of ten nuclear diameters, the repulsive force between the fission fragments is about the same as the force of the earth's attraction on a mass of 4 lbs. These forces fall off rapidly as the fragments separate, but they are maintained for sufficient distances to impart tremendous energies to the two particles into which the uranium atom divides. The total energy acquired by these two particles as a result of their mutual repulsion is readily estimated in terms of their charges,

if some reasonable assumption has been made as to their distance apart at the time of their separation; the result obtained from such a calculation shows that the total energy involved is of the order of 200 MeV. This new process of fission releases much more energy than is set free in any other single atomic process known.

In view of this large energy release, it is rather remarkable that nuclear fission was not discovered earlier. In fact, fission was so different from all previously known nuclear processes that nobody was on the look out for it. There were, indeed, a few occasions on which it was nearly discovered, but by some mischance of experimental arrangement, evidence of its occurrence was obscured.

(2) *The nature of the fission fragments.*

What is the nature of the fission fragments? The mass number of uranium I is 238, so that prior to fission the uranium nucleus has a mass number of 239; its atomic number is 92. We have already mentioned that barium is one of the products of uranium fission and that lanthanum is another; if we assume that the fission fragments sometimes consist of these nuclei and that the atomic numbers of the fission fragments add up to 92, barium must be accompanied by krypton and lanthanum by bromine. But if we determine the total mass of the heaviest known stable isotopes of these pairs of elements, we find that it is 224 in the case of Ba and Kr and 220 in the other case. This leaves, respectively, 15 or 19 mass units for which we have yet to account. An earlier chapter of this book may prompt the supposition that some of the mass has been converted into energy; this is quite true, but as the amount so converted is considerably less than one mass unit, this process has little bearing on the question of the disposal of the total mass of the uranium atom.

It must be remembered, however, that the fission fragments are radioactive to such an extent that they suffer several successive $\beta$ ray transformations before they become stable atoms; this $\beta$ radioactivity is only possible because the primary fission nuclei are much heavier than stable atoms of the same element. Considered in numerical detail, we may have overestimated somewhat the mass number by which the masses of the primary fission nuclei exceed those of stable nuclei, for it is known that one to three neutrons are released in the process of fission, and it is also known that in many cases the original unstable uranium nucleus is formed from $U^{235}$ and so is lighter than we have assumed by three mass units. But even when allowance is made for these possibilities, we find that some of the fission fragments have abnormally

high masses, much higher than those of the artificial radioactive substances which have been produced by means other than nuclear fission.

It is desirable to determine the atomic numbers and mass numbers of the primary fission fragments, and although this problem presents some difficulties because of the short lives of some of the radioactive substances involved, it can certainly be solved. For, if a chain of $\beta$ ray transformations is followed through, the original fission fragment will eventually become an artificial radioactive nucleus the mass and properties of which are known from other experiments; in such a case the two substances will be chemically identical and will also have the same radioactive transformation constants. From the mass number of this substance and the details of the chain of $\beta$ ray transformations, the mass number and atomic number of the primary fission fragment can be determined. For example it is known that one form of the substance which was once thought to be radium and was later found to be barium has a half life which is the same as that of radioactive barium, $Ba^{139}$, prepared by neutron bombardment of the natural barium isotope $Ba^{138}$. This particular example serves to show that eventually the identity of the fission products will be established. Nevertheless, if $Ba^{139}$ is a primary fission nucleus, it is much lighter than would be anticipated in view of the facts stated above.

Little general information is available concerning the identity of the fission products and the proportions in which they are produced. Experiment- have shown that bromine, krypton, rubidium, strontium, yttrium, molyb, denum, antimony, tellurium, iodine, xenon, caesium, barium and lanthanums as well as other elements,* are produced after uranium has been subjected to neutron bombardment. These substances have been detected because they are formed with radioactive properties; in addition there must be non-radioactive elements formed, but these are much more likely to arise from the radioactive decay of other fission products than as primary fission nuclei.

It is of interest to consider briefly the results of experiments in which measurements have been made of the ionization produced by the fission fragments, and from which the energies of these fragments have been determined. Fig. 27 shows some of the results. It will be seen that the most frequent energies of emission are 40 MeV and 85 MeV and that energies differing from these occur frequently. After examining such data it seems reasonable to suppose that fissions result in the production, on one occasion or another, of pairs of most of the elements mentioned above. The process of fission appears to take place in a great variety of ways, and on any one

* The Smyth report states (7.35) that the fission products of uranium include thirty elements.

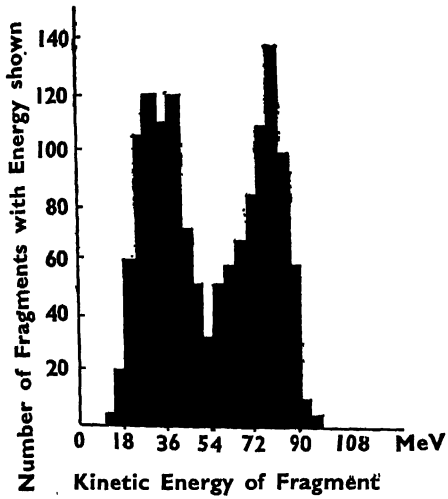



**Fig. 27.** Distribution of kinetic energy of fission fragments.

occasion the identity of the two immediate fission products seems to be determined by chance.

The nature of the fission products is, however, closely related to the energy balance in the fission process. If we consider the phenomenon as a process which transforms the original unstable uranium atom into a number of lighter stable atoms, we see that the energy released in the fission process is to be calculated from the difference between the mass of the uranium atom plus a neutron, and that of the ultimate fission products, i.e., the sum of the masses of the stable atoms which are finally formed from the fission products by radioactive decay. If we assume that a uranium atom of mass 238 absorbs a neutron and then splits into two masses of 140 and 99, we find that the heavier mass is stable when its atomic number is raised by $\beta$ emission to the value of 58; the lighter mass becomes stable when its atomic number is 44. If this happens, the ultimate fission products are then cerium and ruthenium nuclei which have atomic masses of 139.958 and 98.942. If we take the mass of $U^{239}$ as 239.134 we see that there is a disappearance of a total mass of 0.234 mass unit, to which corresponds an energy of 218 MeV. The greater part

of this energy appears as the kinetic energy of the fission fragments; the rest of it is released in the ten β ray transformations which convert the immediate fission fragments into stable cerium and ruthenium nuclei. We could calculate the kinetic energy of the fission fragments directly, if we knew their precise masses. But as the isotopes involved are unusual, and as their lives are so short, it has not yet been possible to obtain this information experimentally, and the best that can be done is to employ masses which are derived by using theories of nuclear structure and the most accurate information available concerning the masses of stable elements.

From such calculations we can obtain an estimate of the energy emitted in the β ray disintegrations which convert the primary fission fragments into stable end-products. The magnitude of this energy depends on the nature of the primary fission fragments, and in a number of cases it will amount to about 40 MeV; in others it departs somewhat from this value. If this figure is appropriate to the case of the fission fragments discussed above—and it should be remembered that the fragments chosen do not necessarily represent a possible fission process—their total kinetic energy will be close to 180 MeV.

We might prefer to calculate the kinetic energy of the fission fragments in terms of the electrical forces of repulsion during their release; this approach to the problem has great advantages over the use of the mass energy equation, but it does not yield a reliable result. For to use it, we require to know the nuclear charges of the fission fragments, and their distance apart and kinetic energy at the moment when they are sufficiently separated to make negligible the attractive forces that earlier held the nucleus together. This is not yet possible, and despite the attractions of calculating the kinetic energy in terms of the forces which give rise to it, the results of such a calculation are too approximate to be of significance.

It is established that the two fission fragments are unequal in mass; one fragment lies usually in a mass range near 140 while the other fragment lies in a mass range in the neighbourhood of 100. It is believed that momentum is conserved in the process of fission; in consequence the lighter fragment carries the larger portion of the energy. For fragments of masses 99 and 140, and a total kinetic energy release of 180 MeV, the lighter particle has an energy of about 105 MeV and the heavier one carries the balance of 75 MeV. These figures are given by way of example only; they depend on so many assumptions and approximations that they can only serve as a rough guide. Nevertheless, the information afforded by Fig. 27 is in general accord with the statements just made. In that figure we see that there is a low energy group of particles with a maximum energy of about 70 MeV and a high

energy group with energies up to 100 MeV*; the sum of these two maxima is reasonably close to our estimate of 180 MeV. The figure shows, however, that not every pair of fission fragments carries this maximum amount of energy; nor is this surprising. For we know that a few neutrons are produced when a fission takes place; furthermore, the primary fission fragments may be formed in an excited state, in which case they carry energy which might have appeared as kinetic energy of the fission fragments, but which in fact is emitted as $\gamma$ rays immediately following fission and before the first $\beta$ transformation. When proper account is taken of these possibilities, we will obtain for the mean kinetic energy of the fission fragments a value considerably less than that derived from calculations such as have been described above. Nevertheless, experiment, in confirmation of approximate calculations, shows without doubt that the fission fragments are emitted with far more kinetic energy than is carried by the particles released in any other known nuclear reaction.

(3) *The theory of the fission process.*

Before we discuss further the available experimental data concerning fission, it is desirable to consider some theoretical aspects of the problem. Our theories of nuclear reactions are very much influenced by the work of the Danish physicist Niels Bohr, and in the particular case of fission itself by the work of Bohr and Wheeler,[2] published in 1939. In the course of what follows, an outline will be given of Bohr's theories, and of their application to nuclear fission as explained in the papers by Bohr and Wheeler.

Let us turn for a few moments to a discussion of present-day views of nuclear structure. It is believed that an atomic nucleus is composed of neutrons and protons. If we consider, for example, $U_{92}^{239}$, we see that this nucleus must consist of 92 protons and 147 neutrons. The protons are of course positively charged and the consequent electrostatic forces must bring about intense mutual repulsion between the protons in such a nucleus. Since many nuclei are found to be stable, we must postulate other forces which hold the nucleus together, forces which arise from attractions between neutrons and from attractions between neutrons and protons. It is difficult to appreciate the nature of these forces, but as the protons themselves repel one another powerfully, it is clear that the neutron-neutron and neutron-proton forces must also be intense when the interacting particles are as close as they are in a nucleus; furthermore, the range of these forces must be short, for otherwise an $\alpha$ particle would not be able to escape from a radioactive

* Fig. 27 is derived from data given by Booth, Dunning and Slack[3]. It is probable that the energy scale attached to Fig. 27 underestimates the energy of the fission fragments.

nucleus. It is thought that there are also short range proton-proton attractive forces, but although these may help to hold the nucleus together, they must be smaller than the electrostatic repulsive forces between protons. It should be mentioned here that β particle emission is to be regarded as involving the conversion of a neutron into a proton and an electron; the electron is ejected from the nucleus and the proton remains within, where it contributes an additional unit to the atomic number of the nucleus.

Although we occasionally talk about individual particles in a nucleus, it is sometimes better to think of the nucleus as a single entity and to consider the energy of the nucleus as a whole rather than the energy of the individual particles of which it is composed.

The view which is at present held—a view that has led to fruitful predictions concerning the behaviour of the nucleus—is that the nucleus may be likened to an electrically charged drop of liquid. Here there is a force of surface tension which holds the drop together; the molecules of the liquid have a perfectly definite mean energy, but individually they move about in a random fashion with velocities which differ widely. The mean energy of motion of the molecules depends on the temperature of the drop, and for those molecules with energies near this mean value, escape is effectively prevented by the surface tension forces. On the other hand, a particularly fast molecule may have sufficient speed to pass through the force system that gives rise to the effects of surface tension, and if its motion is suitably directed it will escape. In any drop of liquid there will always be a few of these fast molecules—they gain their high energy quite by accident as a result of favourable collisions with other molecules—and in consequence, in the case of a volatile liquid, there will always be molecules escaping through the surface of the drop.

It must not be imagined that the nucleus is to be regarded as behaving in exactly the same way as does a drop of liquid—there are too few particles in a nucleus to make it possible to carry the analogy very far—but there is sufficient similarity to enable us to use the analogy to obtain an understanding of the process of heavy particle emission by a nucleus. As we shall see, the analogy also gives a useful picture of the mechanism of fission.

Let us consider the process of neutron emission. First of all we require to know the binding energy of the neutron. This is the amount of excess energy possessed by a nucleus which has just captured a very slow neutron, or, looking at it from the viewpoint of the mass energy equation, the energy equivalent of : mass of neutron + mass of original nucleus—mass of nucleus formed by neutron capture. If this amount of energy is supplied to a nucleus, the emission of a neutron is energetically possible but it does not follow that a neutron will escape, for the energy tends to be shared out amongst

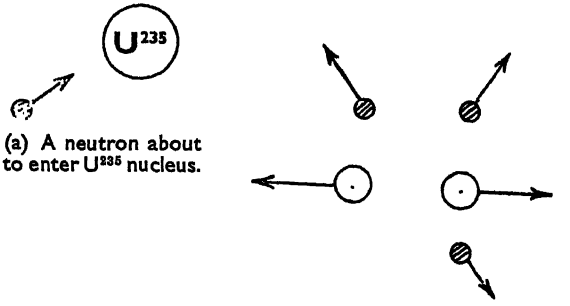
all the particles in the nucleus ; neutron emission will occur only if one neutron obtains sufficient of the total energy of the nucleus to enable it to overcome the attractive forces of the rest of the nucleus and escape from the region in which they act. The analogy between this process and the escape of a molecule from a liquid drop is close indeed, for just as with the neutron, escape of a molecule can occur only if a sufficient amount of kinetic energy is communicated to one individual molecule. When we give a little extra heat to a drop, we increase the total energy of the molecules of which one or two may thereby be enabled to escape. But if the molecules do not carry off the extra energy by escaping from the drop, this energy will be lost, perhaps by radiation. Somewhat similar alternatives are available in the case of a nucleus to which has been communicated an energy in excess of the neutron binding energy ; if a neutron does not obtain sufficient of the nuclear energy to enable it to escape, the excess energy of the nucleus will be emitted as $\gamma$ rays. In the case of the nucleus the excess energy is quickly disposed of, for the $\gamma$ ray emission occurs within about $10^{-12}$ sec. of the moment at which the excess energy is supplied, unless of course the neutron is emitted previously.

When we consider the liquid drop analogy of the fission process, we need to take account of the electrical charge which the drop must be supposed to carry. It is well known that an electrically charged soap bubble tends to expand owing to mutual electrical repulsions, and in the case of a charged drop the electrification gives a force in opposition to the surface tension forces which hold the drop together. It we gradually increase the amount of the electric charge, we will similarly increase the disruptive forces, and a time will come when the drop is unstable and flies apart of its own accord. Even with a smaller charge than this—a charge that is not large enough to make the drop unstable—the drop may in certain circumstances be able to break up. For if the drop is distorted suitably and sufficiently, a configuration may be attained in which the electrical disruptive forces are more than sufficient to overcome the forces of surface tension, which are now unable to hold the drop together. The drop breaks into two portions with, in addition, a few small droplets which perhaps arise from portions of the liquid at one time near the line of division of the drop. It should be noted that the drop was initially stable and that division occurred as a result of a finite amount of distortion. To achieve this, energy must be communicated to the drop, the amount of energy required depending on the relative magnitudes of the electrical and surface tension forces. For a drop of given size and surface tension, the greater the electrical charge, the smaller will be the energy needed to produce the distortion that results in the break up of the drop.

Bohr views nuclear fission as being similar to the process just described.

The equivalent of the surface tension force is the neutron-proton and neutron-neutron attractive forces ; the charge of the protons in the nucleus is responsible for the disruptive electrical force. According to the theories of Bohr and Wheeler, nuclei with charges much greater than 92 are likely to be unstable and so incapable of existence. If Z denotes the nuclear charge and A the mass number of a nucleus, it has been estimated that this nucleus cannot be stable if $\frac{Z^2}{A}$ is more than some 30% greater than the value appropriate to $U^{238}$, that is, $\frac{(92)^2}{238}$. From this calculation, it appears that the heavier elements are near the condition of instability, and it is to be anticipated that relatively small distortions may be sufficient to cause them to disrupt. The argument suggesting that fission occurs as a result of a sufficient distortion is similar to that given for the case of the liquid drop. Here the distortion causes a considerable decrease in the neutron-neutron and neutron-proton binding forces and a much smaller one in the electrical forces of repulsion. From a small distortion the nucleus may recover ; from a larger one it may recover or it may split in two ; from a still larger distortion of a suitable kind the nucleus will in no case maintain its existence. It is to be noticed that fission will not occur unless the nucleus is first supplied with sufficient excess energy to bring about the necessary distortion, and even if this amount of energy is provided the distortion occurring may not be such as to give fission, and the excess energy of the nucleus may be radiated. If we again describe a nucleus with excess energy as an excited nucleus, we may say that fission can occur only if the nucleus possesses sufficient energy of excitation ; as, however, the nucleus is in any case liable to lose its excess energy by radiation or neutron emission within $10^{-12}$ sec. of acquiring it, if fission does not occur within a very short time after the excitation of the nucleus, it will not occur at all. In Fig. 28 is given a sketch of the stages which are believed to occur in the process of nuclear fission.

Which nuclei are likely to undergo fission upon neutron bombardment ? We will suppose that the element being bombarded captures a neutron ; as a result it will have an amount of excess energy equal to the neutron binding energy plus the kinetic energy of the neutron, for, as explained above, the neutron binding energy is the energy of excitation of the nucleus when a slow neutron is captured by it. Now there will be negligible probability of fission unless the excitation energy of the nucleus is as great as that required to distort the nucleus to the extent necessary to permit fission. This latter energy, which is denoted by $E_t$, is found to depend on $\frac{Z^2}{A}$ ; in Bohr and




(a) A neutron about to enter $U^{235}$ nucleus.

(b) Uranium nucleus after neutron capture. The excess energy (excitation energy) of the nucleus causes distortion which leads to fission.

(c) After fission : Two fission fragments move in opposite directions. In this case there are three fission neutrons.

**Fig. 28.** Three stages in the nuclear fission process.

Wheeler's paper are given values of $E_f$ and of neutron binding energies for a number of heavy nuclei. If the neutron binding energy exceeds $E_f$, any captured neutron at all will be able to cause fission, and on occasion it will do so. But if $E_f$ exceeds the neutron binding energy, fission can be brought about only by neutrons having a kinetic energy greater than the amount by which the neutron binding energy falls short of $E_f$. In Table 1 are given Bohr and Wheeler's values of $E_f$ and of neutron binding energies for nuclei formed from various heavy elements by neutron capture. The table also lists values of $\frac{Z^2}{A}$ for the five nuclei listed in the second column.

Table 1.

| Original nucleus | | Nucleus after neutron capture | Neutron binding energy in MeV | $E_f$ MeV | $\frac{Z^2}{A}$ |
|---|---|---|---|---|---|
| Thorium | $Th^{232}_{90}$ | $Th^{233}_{90}$ | 5.2 | 7.0 | 34.8 |
| Uranium I | $U^{238}_{92}$ | $U^{239}_{92}$ | 5.2 | 5.9 | 35.4 |
| Proto-actinium | $Pa^{231}_{91}$ | $Pa^{232}_{91}$ | 5.4 | 5.5 | 35.7 |
| Actino-uranium | $U^{235}_{92}$ | $U^{236}_{92}$ | 6.4 | 5.4 | 35.8 |
| Uranium II | $U^{234}_{92}$ | $U^{235}_{92}$ | 5.4 | 5.2 | 36.0 |

If these figures are correct, in the case of uranium II and actino-uranium any neutron captured, slow or fast, is capable of giving the necessary distortion which preceeds fission. To bring about fission of protoactinium, the bombarding neutrons must have an energy of at least 0.1 MeV; energies of 0.75 MeV or more are necessary in the case of uranium I, and in the case of thorium neutrons of still higher energy are required.

By way of concluding our examination of this part of Bohr and Wheeler's paper, it is desirable to discuss briefly the likelihood of fission of a heavy nucleus that has captured a neutron. We do this by considering an excited nucleus and the way in which it disposes of its energy of excitation. Subsequently, in order to determine the consequences of neutron capture, we consider the various important possibilities for a nucleus which has excitation energy in the appropriate range. In the discussion that follows we shall assume that the nucleus disposes of surplus energy by one or other of the processes : emission of radiation, emission of a neutron, and fission.

Let us first assume that $E_f$, the excitation energy which must be available if fission is to occur, is large compared with $E_n$, the neutron binding energy. We now assume that the nucleus possesses a definite excess energy without specifying the means by which it acquired it. Then for excitation energies lower than $E_n$, emission of radiation occurs in every case ; there is no other way in which the nucleus can dispose of its excess energy. But once $E_n$ is exceeded, alternative processes are possible. With energies of excitation only a little greater than $E_n$, relatively few excited nuclei will emit radiation ; for although this process can still occur, it requires a longer time than does neutron emission, which is so much quicker that it is almost the rule. The fraction of excited nuclei radiating energy, and its dependence upon their excitation energy, is shown in Fig. 29a.

For excitations higher than $E_f$, fission also becomes possible. At these high excitation energies, however, neutron emission occurs so rapidly that there are relatively few cases in which fission actually occurs, rapid though this process is. The fractions of the total number of excited nuclei disposing of their energy by neutron emission and by fission are shown in Fig. 29b and c. These sketches show that for excitations greater than $E_f$, fission and neutron emission are competing processes, and that fission is the less likely of the two.

We now consider the more important case in which $E_f$ is less than $E_n$. The dependence of radiative emission, neutron emission, and fission on excitation energy are shown in Fig. 30a, b and c respectively. In this case, also, fission occurs as soon as the excitation energy exceeds $E_f$, and from here, up to an excitation energy $E_n$, fission increases in importance at the expense of radiative emission. At excitations above $E_n$, fission and neutron emission

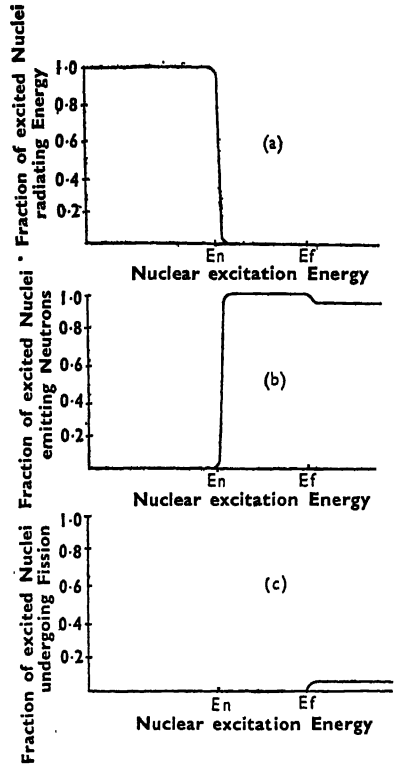



**Fig. 29.** The behaviour of a nucleus possessing excitation energy. (Ef exceeds En.)

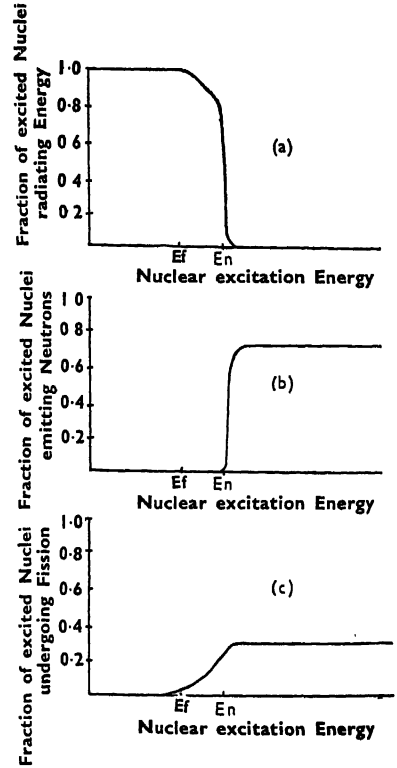



**Fig. 30.** The behaviour of a nucleus possessing excitation energy. (En exceeds Ff.)

become the only important processes, and once again neutron emission is the more likely. On this occasion, a reasonable fraction of highly excited nuclei give rise to fission, in contrast to a much smaller fraction in the case first discussed in which $E_f$ was greater than $E_n$.

When the nuclear excitation results from neutron capture, it will exceed $E_n$. If $E_f$ is greater than $E_n$, fission can result only for neutrons with kinetic energies greater than $E_f - E_n$, and, as we have seen, even then fission occurs much less frequently than does the emission of neutrons. On the other hand,

if $E_n$ is greater than $E_f$, the capture of a slow neutron will give sufficient excitation to make fission possible. For these neutrons, which give an excitation energy $E_n$, and for faster neutrons, fission is reasonably likely.

This discussion shows that fission is most readily achieved with substances for which $E_f$ is less than the neutron binding energy, and from what has been said, and from the data given in Table 1 we see that $U^{234}$ and $U^{235}$ are most likely to exhibit fission on neutron bombardment. For both these elements, but especially for $U^{235}$, fission will take place on bombardment by slow neutrons.

It now remains to consider some of the other topics treated by Bohr and Wheeler. In discussing the total energy released in a fission process, they point out that nuclei of mass number greater than 110 will yield energy if they can be made to break into three nearly equal parts; in the case of uranium, calculation showed that the available energy in this hypothetical process is actually greater than that released when the nucleus breaks into two parts as in fission. Such calculations serve to remind us that a process which theoretically will yield energy may or may not occur in practice. Certainly fission is a process which releases energy and this is one reason for its occurrence, but the most important factor is the possibility of producing sufficient nuclear distortion to initiate the process that releases this energy.

The theories of energy release in fission show that the fission fragments acquire the maximum total kinetic energy when the two fragments are of nearly equal mass. They also show that for a given mass of one fragment there is only a small range of nuclear charge numbers (atomic numbers) which gives a release of kinetic energy at all near this maximum value; outside this range of charge numbers, more of the energy of fission appears as internal energy of the fission fragments—to be released subsequently in radioactive $\beta$ ray transformations—and less as kinetic energy. As has been mentioned already, it appears that the fission process occurs in a wide variety of ways, and that fission into two fragments with the same energy—in which case they must also have the same mass—is unlikely, if indeed it ever happens.

Bohr and Wheeler have made estimates of the energies released in the $\beta$ ray emissions that transform the fission fragments into stable nuclei. The results obtained give us the masses of the radioactive fission nuclei, and of the substances produced from them by successive $\beta$ ray transformations—nuclei with mass numbers higher than the values appropriate to stable nuclei carrying the same charge. In general, the energy released in successive $\beta$ ray transformations is believed to decrease uniformly as the nucleus nears its final stable atomic state, but in detail only nuclei of odd mass number have $\beta$ ray emission energies varying in this way. In the case of nuclei of even

mass number, the energy of β ray emission is correctly given only after the addition of a further quantity, the value of which depends on whether the initial nucleus has an odd or even atomic number. The figures obtained show that these β ray transformations release energies of up to 15 MeV and that, although the average β ray emission energy is in the neighbourhood of 4 MeV, cases are not uncommon in which the energy of the β ray transformation considerably exceeds this value.

In the light of these theories, we have next to consider further some of the available experimental data concerning nuclear fission. In particular, our interest must be directed to the experimental values of the cross sections for the various phenomena occurring when uranium is bombarded by neutrons. Furthermore, we must examine, in some detail, the origin and properties of the neutrons produced during and after uranium fission. These two matters, both of the utmost importance from the point of view of the development of atomic energy, are dealt with in the next chapter.

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## CHAPTER X

# RELEASE OF ATOMIC ENERGY: CHAIN REACTIONS

(1) *The nature of a chain reaction.*

The contents of the previous chapter are sufficient to stress the novelty of the fission process. This new mode of atomic disintegration was of scientific importance because it gave fresh information concerning the properties of the nucleus and in addition provided many elements—the fission products—in unusual radioactive forms; furthermore, it was of great significance because it provided a process which it was believed might permit use of nuclear energy. The individual fission process was produced by a neutron; the act of fission yielded large amounts of energy and more neutrons, and in suitable circumstances, some of these latter neutrons could bring about further fissions. The available knowledge of fission suggested the possibility of a " chain reaction " in which a single neutron would cause the nuclear fission of a uranium atom, as a result of which a chain of fissions might be produced throughout the mass of uranium.

Before we discuss such a reaction—it is called, as stated above, a chain reaction—we should introduce a new term. This is k, the reproduction factor. It represents the average number of neutrons which arise from one fission and which themselves produce fission. If a million fissions produce two million neutrons of which 999 000 produce further fissions, k is 0.999. If, on the other hand, a million fissions give a million and a half neutrons of which 1 001 000 produce further fissions, the reproduction factor is 1.001.

To form a clear but simple picture of the chain reaction, we may assume a reproduction factor of 2 so that each fission gives rise to two neutrons that cause further fission. From these two fissions will arise four, and from these eight; at the tenth stage of the chain—it is sometimes useful to call this the tenth generation—there are more than one thousand fissions produced and at the twentieth more than a million.* This picture is too simple; not only is it improbable that our chain grows at the rate assumed, doubling itself at every stage, but it is unlikely that every fission—or even every hundred fissions—produces the same number of neutrons, or indeed that a given number of neutrons produces a constant number of fissions. Nevertheless, if it is arranged that, on the average, one fission is followed by just more than one subsequent fission, we will have a chain reaction which is capable of

* The actual numbers are $2^{10}$ and $2^{20}$ respectively.

building up and of maintaining itself. Even if every hundred fissions is followed, on the average, by only 101 fissions, corresponding to a reproduction factor of 1.01, the chain will build up; after one thousand neutron generations, the rate of fission will have increased in amount by a factor in excess of 20,000. Such a chain reaction will build up in this way until other factors, which we have not yet considered, come into play and diminish the rate at which the reaction increases in intensity.

In the case of uranium it was believed that no more could be achieved than a reproduction factor slightly greater than unity; but as fission was believed to occur almost instantaneously it was thought that the reproduction time would be small and that a chain reaction might grow with tremendous rapidity. Quite clearly, if this was achieved, enormous quantities of heat energy would be produced, for if the fission of a single uranium atom yields 200 MeV, the fission of about 1 lb. of these atoms will yield $10^7$ kWh, or over two million times as much heat energy as is produced by burning 1 lb. of coal. Considerations of this type prompt two questions. Will the process work, and if it will, can it be controlled, or will the heat be yielded in such a way that the reacting uranium and the apparatus associated with it are dissipated by an explosion of unparalleled magnitude? These questions were being asked early in 1939 after the discovery of nuclear fission. Too little was then known of the details of the process to enable an answer to be given. Further experiments were needed to investigate the details of the reaction occurring when a neutron brought about the fission of a uranium atom. Let us see what conclusions were drawn from the experiments made.

(2) *Substances capable of giving a chain reaction.*

The substance of greatest interest is uranium, but as Bohr's theories deal also with thorium and protoactinium, it is desirable to mention first what is known of their behaviour when they are subjected to neutron bombardment.

The case of thorium is simple; the single natural isotope, $Th^{232}$, exhibits fission only when it is bombarded by high energy neutrons possessing energies greater than 1.7 MeV. As the fission cross section is not very large, a fast neutron which enters a mass of thorium is more likely to be slowed down than to cause thorium fission, and for this reason a chain reaction is unlikely to occur. According to published information, the organization for developing the atomic bomb gave little attention to the possibilities of making use of thorium, despite the fact that this element is more plentiful in nature than is uranium. In view of the way in which the atomic bomb organization appeared to try every method that could conceivably work, it is to be inferred that at the present state of knowledge it is not possible to produce a fission chain reaction using thorium.

The case of protoactinium is somewhat different. According to Bohr's theories, this nucleus should exhibit fission on bombardment by neutrons with energies in excess of 0.1 MeV. Experimentally it is found, according to the Smyth report,[1] that this material gives fission only when bombarded by fast neutrons of unspecified energy. On account of the relative scarcity of protoactinium, it was not considered as a source of atomic energy, but even if it had been available in quantity, its failure to react favourably to bombardment by slow neutrons would have made its use relatively unattractive compared with that of uranium.

Let us then consider the reactions of uranium when bombarded by neutrons. It should be remembered that there are three long-lived uranium isotopes, $U^{238}$, $U^{235}$ and $U^{234}$, and that natural uranium consists of a mixture of these three; the commonest isotope is the heaviest which is 139 times as plentiful as $U^{235}$ and about 16 000 times as plentiful as $U^{234}$. In any reaction involving natural uranium, we can usually neglect the effects of $U^{234}$ but we must bear in mind that the amounts of $U^{235}$, though small, are often sufficient to make their presence felt.

Early experiments showed that uranium gives fission when bombarded by either fast or slow neutrons. When fast neutrons are employed, fission occurs, in the main, from $U^{238}$, which forms $U^{239}$ on neutron capture. For 2.5 MeV neutrons, the cross section for this process[2] has been measured and is about $5 \times 10^{-25}$ cm.$^2$, a figure that shows that these neutrons will have a mean path length before causing fission of about 0.5 metre. In view of this small fission cross section, and the fact that it falls in value with the energy of the neutrons, it is necessary to consider alternative processes in which fast neutrons may be involved, for if these processes have appreciable probability, they may prevent the occurrence of any substantial numbers of fissions. In fact this is what happens. For although a neutron loses only a small fraction of its energy as a result of an elastic collision with a uranium nucleus, such collisions will occur frequently and will result in the slowing down of fast neutrons. Furthermore, every capture of a fast neutron does not result in fission, especially in the case of neutron capture by $U^{238}$. In the majority of cases, neutron capture by such a nucleus is followed by the emission of a neutron, usually with less energy than the one which was captured. When account is taken of these interactions between a mass of uranium and fast neutrons, it will be seen that few of these neutrons are likely to cause uranium fission. From the point of view of causing a chain reaction with fast neutrons in $U^{238}$, there are negligible prospects unless it happens that each uranium fission results in the production of many neutrons, each with sufficient energy to cause further fissions of $U^{238}$. And this does not occur.

Now that we have considered the consequences of bombarding uranium with fast neutrons, let us consider the results when slower neutrons are used. For neutrons with energies below about 0.6 MeV there are very few fissions and almost all of these arise from neutron capture by $U^{235}$ nuclei. For quite slow neutrons, however—those with energies close to 25 eV—there is very strong absorption by $U^{238}$ nuclei. The process is a resonance radiative capture with a capture cross section[3] of $10^{-21}$ cm.$^2$ corresponding to a mean path before capture of only 0.2 mm.; the resulting nucleus is $U^{239}$, a substance which emits $\beta$ rays and has a half life of 23 minutes. The capture process which gives rise to $U^{239}$ has turned out to be of the greatest importance in the development of the atomic bomb; it arises at present because it absorbs neutrons that would otherwise be reduced to thermal energies. Now neutrons of thermal energies have two possibilities; either they are captured by $U^{238}$ nuclei to form $U^{239}$ or they give rise to fission of $U^{235}$ nuclei. Despite the fact that in natural uranium there is only one $U^{235}$ atom in every 140 uranium atoms, two $U^{235}$ fissions occur for every thermal neutron captured by $U^{238}$.

If then we bombard natural uranium with fast neutrons, there will be a few fissions caused by fast neutrons which are not involved in other interactions; most neutrons will be slowed down and their fate must be considered in the light of possible interactions between uranium nuclei and slower neutrons. As the slowing down process occurs gradually as a result of collisions with uranium nuclei, most neutrons will eventually be reduced in energy to values sufficiently close to that of the resonance absorption level of $U^{238}$ to be captured and to form $U^{239}$. Those few neutrons which avoid capture by $U^{238}$ cause fission of $U^{235}$.

Although the numerical data are incomplete, it is apparent that in order to achieve a single fission from natural uranium, some few fast neutrons must fall upon it; unless this fission results in the production of thermal neutrons or of an appreciable number of fast neutrons, a chain reaction will not be possible. The main difficulty in the way of achieving a chain reaction is the presence of $U^{238}$ with its strong resonance absorption level in the neighbourhood of 25 eV. Because of this interaction between slow neutrons and the commonest uranium isotope, many neutrons are captured by it and not enough are left to maintain a chain reaction depending principally on fission of $U^{235}$.

(3) *Fission neutrons.*

The last section has described the main properties of natural uranium relative to its interactions with neutrons. Before we discuss other matters which

determine the possibility of achieving a chain reaction, it is desirable to consider the vague information available concerning the neutrons emitted in the fission process. Accounts have been given of attempts to determine the average number of neutrons emitted per fission; it is not difficult to make approximate measurements of this quantity, but accuracy is hard to achieve. Some published measurements suggest that there are more than two neutrons per fission but it is not possible to be definite upon this point. The Smyth report[4] gives the number as being from 1 to 3, and does not appear to discuss further a quantity which is of the utmost importance in any detailed consideration of the possibility of achieving a chain reaction and of releasing atomic energy on any appreciable scale. From the point of view of this book, the number of neutrons emitted per fission is of general interest only, and we shall assume, without any belief that the figure is correct, that there are emitted on the average two neutrons per fission. We next require information concerning the energy of these neutrons and the time in the fission process at which they are released.

In view of the great variety of the fission products, it is not to be anticipated that the fission neutrons will be released with uniform energy, and it is not surprising to find that the energy of the neutrons is spread over a considerable range. To make reliable detailed measurements of neutron energies is not very difficult as long as neutrons of high energies only are involved; it is a much more troublesome experiment for neutrons with energies well below 1 MeV and for this reason the data available appear to be restricted to the neutrons of high energies. It seems, however, that a few of the neutrons emitted have energies up to 3 MeV and that from this point down to about 0.5 MeV there is a steady increase in the number of neutrons emitted as the energy of emission decreases. Looking at this information from the point of view of the possibility of obtaining a chain reaction with $U^{238}$, it is apparent that a small but appreciable fraction of the fission neutrons are emitted with sufficient energy to cause fission of $U^{238}$, but that the majority of the neutrons have considerably lower energies. Quite apart from the fact that there is a rather large chance that a fast neutron will not give rise to fission of $U^{238}$, it appears that a chain reaction depending on this material is not possible because each fission does not yield one neutron with enough energy to cause a further fission of $U^{238}$. The prospects with this material are even less favourable than with natural uranium where, as we found, a chain reaction was not possible because of the radiative neutron capture by $U^{238}$. The only other possibility which is immediately obvious is to use $U^{235}$; as we shall see later, a chain reaction is indeed possible with this material, but in order to achieve it $U^{235}$ must be separated in some quantity from natural uranium.

The origin of the fission neutrons is a matter of some interest and impor-

tance, and although there is some uncertainty of detail, it is known that most of the neutrons are emitted at the instant of fission. If we again compare an atomic nucleus with an electrified liquid drop, we see that some of the fission neutrons may be analogous to the small droplets which are found to be produced when a drop of liquid divides into two major parts. Alternatively, the neutrons may arise from the fission fragments themselves, probably before they have lost much of the kinetic energy arising from their mutual repulsion. It is to be remembered that a fission fragment of mass 100 and energy 100 MeV has a velocity of $1.4 \times 10^7$ metres per second, or about 5% of the velocity of light, and that even in air its path length is only of the order of 3 cm. while its time of flight is less than $10^{-8}$ sec. Usually, however, the fragment loses its energy inside a piece of uranium, and in this case its path length is of the order of $10^{-5}$ cm. while its energy will be lost in a time interval of about $10^{-13}$ sec. We have already seen that neutrons are emitted from an excited nucleus in an interval of time of this order of magnitude, and it is to be expected that if the fission fragments do indeed emit neutrons, they will do so before they have lost much kinetic energy, and that the neutrons will consequently carry with them their share of the initial kinetic energy of the fission fragment. Investigations of the energy of emission of the fission neutrons give support for the view that these are emitted from nuclei moving at high speed, and this means that these neutrons must arise within a period of about $10^{-12}$ sec. or less after the capture of the neutron which caused fission. Not only is fission itself a rapidly occurring process; the great majority of the neutrons resulting from it arise so soon after its initiation that their emission must be considered as part of the fission process itself. But not all of the fission neutrons are in this position. Some few of them, little more than 1% of the whole, are emitted a short time after fission; they are known as delayed neutrons.

These delayed neutrons have been studied in detail and it has been found that after intense neutron bombardment of a mass of uranium, delayed neutrons can be detected up to a period of 15 minutes after the termination of the bombardment. The rate of emission of delayed neutrons gradually becomes smaller throughout this period, and studies of this rate show that it decreases with time in much the same way as does the activity of an ordinary radioactive substance. It is found, however, that it is necessary to assume that the delayed neutrons arise from a number of different kinds of nuclei, for the observed neutron activity is best explained as arising from four materials, each of which has its appropriate rate of transformation, with half lives ranging from 2.5 sec. to about 1 minute. At first sight one might suppose that here was a new type of radioactivity in which neutrons were emitted instead of the more usual $\alpha$ or $\beta$ particles; a moment's consideration of the

rapidity of emission of a neutron from an excited atom shows that some alternative explanation is more probable. It will be remembered that the primary fission products are radioactive substances of short half life, a fact that suggests that the delayed neutrons arise from nuclei formed after radioactive transformation of some of the fission products. On this view, the relatively slow rate of release of these few neutrons occurs because of the slow rate of formation of the nuclei from which they come. One doubt may remain; where do these product nuclei obtain sufficient surplus energy to make possible the emission of a neutron? If the neutron is emitted from a nucleus formed after the radioactive emission of a $\beta$ particle, the total energy released in the radioactive transformation must be sufficient to provide the $\beta$ particle energy and to leave the product nucleus with an energy exceeding the neutron binding energy. It is apparent then that neutron emission will be possible only after $\beta$ particle transformations in which the maximum available energy is very large; furthermore, in every instance in which a neutron is emitted from a nucleus, the $\beta$ particle preceeding it must withdraw only a small portion of this energy. Bohr's calculations suggest that some of the radioactive fission products release sufficient energy in $\beta$ particle transformations to make possible the emission of a neutron.

It may be imagined that these delayed neutrons, comprising only about 1% of those emitted in nuclear fission processes, are so few in number as to be of no real significance. In some cases this is precisely the position, but on the other hand, there are cases where the existence of these delayed neutrons is a factor of great advantage and importance.

(4) *Conditions for achieving a chain reaction.*

Now that we have discussed the properties of the fission neutrons, we are in a better position to complete our consideration of the conditions which determine the possibility of a chain reaction. The remarks already made are sufficient to show that such a process will not be easy to achieve in practice, and for this reason we shall discuss a hypothetical case in which we imagine that there is available a supply of a material which has properties similar to those of $U^{235}$ in that it has a large capture cross section for thermal neutrons and that on capture of these neutrons fissions take place. It is convenient to have a name for a material with these properties; the term fissionable material is appropriate. We shall suppose that this material is suitably disposed in a substance– called a moderator—which quickly slows down fast neutrons so as to ensure that they are captured as thermal neutrons by the fissionable material. The mixture of this material and the moderator, from which we hope to obtain atomic energy, we shall call the reacting mass. Let

us see how best to arrange these materials so as to encourage a chain reaction.

We shall suppose that the fissionable material has a fission cross section for thermal neutrons* of $3 \times 10^{-22}$ cm.$^2$ so that such neutrons have a free path of about 0.7 mm. in the pure material. Because of the presence of the moderator, any fast neutron produced as a result of a fission will quickly be slowed down and will then be captured by an atom of the fissionable material. If, then, a neutron once causes a fission, the resulting neutrons, which we assume to be two in number, will be slowed down and will subsequently cause the fission of two further atoms. On the basis of this simple view, the chain reaction will multiply quickly, at a rate depending upon the average time which elapses between the emission of a fission neutron and the subsequent fission brought about by this neutron.

The view we have taken is unduly simple, a result of assuming that every neutron produced brings about a further fission. In any practical system a neutron may escape from the reacting system by passing through its boundary; it may be absorbed in the moderator or in some impurity in the reacting mass, or it may cause further fissions. Only the last process is desired, but the others are inevitable and in some cases they will prevent the occurrence of a chain reaction.

The likelihood of the escape of a neutron depends on a number of factors, including the size and shape of the reacting mass and the position in it at which the neutron originates. It also depends on the average distance a neutron moves between its places of emission and absorption; for if this distance is small, only those neutrons formed on the surface of the reacting mass, or very near to it, will have any reasonable probability of escape. Other things being equal, then, we should arrange that neutrons are absorbed as close as possible to the place where they are released; this is best done by slowing the neutrons to those energies for which the active material has a very large fission cross section. Fast neutrons from an appreciable volume of the reacting mass have a large chance of escape, but ones that are slowed down will almost certainly be captured in the fissionable material and give rise to fission. When the best arrangements have been made in this respect —and they will involve some loss of neutrons because of absorption in the moderator—there will still be other ways in which the loss of neutrons from the reacting mass can be diminished.

In order to achieve a chain reaction we have to arrange that, on the average, each fission is followed by a further fission. To determine whether this happens we suppose that one neutron is produced in each cubic centimetre of

*The value chosen for this cross section is about that appropriate to pure $U^{235}$ (Compare Bohr and Wheeler[5]).

the reacting mass; we then follow the fate of these neutrons in order to see whether or not they result in an increase in the total number of neutrons. It is clear that neutrons produced at the centre of the mass will have negligible chance of escape from the surface; they either cause fission or are lost because of capture processes which do not result in fission. But a neutron formed near the surface of the reacting mass has the same possibilities of fission or of capture if it goes inwards, and the additional possibility of complete loss if it goes outwards. Clearly no chain reaction can succeed unless a fission in the centre of the reacting mass is able to produce enough neutrons to cause a further fission; even if this condition is just satisfied, a chain reaction can only occur if there are no neutrons lost at the surface of the mass, a state of affairs which can never be achieved. Nevertheless, if we find that in the centre of the mass a single fission results in enough neutrons to ensure just more than one fission, we can achieve a chain reaction if we make the reacting mass of sufficient size, for it is only necessary to arrange that the excess of neutrons produced in regions where they cannot escape from the mass is large enough to make up for those that do escape. As has been mentioned already, the only neutrons that are likely to escape are those formed near the surface of the reacting mass; if then we imagine that there is one neutron produced in every cubic centimetre of the reacting mass, the number of neutrons which escapes from the mass is proportional to its surface area, and the total number of neutrons produced is proportional to its volume. Any increase in dimensions of the reacting mass will increase the volume more rapidly than the surface area, and so the volume in which excess neutrons are produced increases by a greater amount than does the volume near the boundary where the loss is excessive.

This discussion indicates immediately the most favourable shape for the reacting mass. It should be a sphere, because this is the figure for which the ratio of volume to surface area is greatest. If a reacting mass is made in the form of a sphere, a chain reaction will be possible with a smaller amount of fissionable material than is required to achieve a chain reaction in a mass of any other shape, and for this reason any practical reacting mass is likely to be made as nearly spherical as other conditions allow.

Before we leave this subject we should note that there is a device by which we can reduce the loss of neutrons at the surface of the reacting mass. If it is completely surrounded by a material which scatters neutrons, it is possible to return to the reacting mass some neutrons which would otherwise be lost. This shell of neutron-scatterer is called a reflector; in some circumstances carbon has been used for the purpose. It will be appreciated that the reflector can return only a fraction of the neutrons which fall upon it; its

purpose is to scatter back into the reacting mass as many neutrons as possible, and for this reason a reflector should possess a high scattering cross section and a very small neutron capture cross section.

(5) *Nuclear energy from the sun.*

These considerations of size and shape of a chain reactor are illustrated by the sun, where atomic energy is being produced on a very large scale. The interior of the sun is believed to be at the very high temperature of $2 \times 10^7$ °C., and at this temperature the average kinetic energy of an atom is about 2,000 eV ; some small fraction of the atoms in the sun will have much greater energies, and it is the nuclei of these atoms which are able to take part in a series of nuclear reactions that results in the conversion of hydrogen into helium, a process which liberates about 30 MeV for every helium atom formed.

If this simple picture is accurate, in every cubic centimetre of the sun about 10,000 helium atoms are formed every second, and about $10^7$ watt of power is thereby developed ; when we determine the total amount of energy produced throughout the sun, we find that it is sufficient to supply the enormous quantities of heat that are radiated, and so it is able to maintain the interior of the sun at a temperature at which these atomic transformations can take place on a necessary scale. It is interesting to note that if the sun were only half its present size, there would need to be double the present rate of production of helium in every cubic centimetre in order to maintain its surface at the present temperature ; if the surface layers of the sun did not act as efficient reflectors of heat, it would not be possible for the interior of the sun to maintain itself at a temperature at which there was any appreciable liberation of atomic energy.

The size of the sun makes possible types of chain reactions that can hardly occur on the earth, and it is for this reason that we have to depend on neutrons in a manner which appears to be unnecessary in a tremendous body of matter at a high temperature. It is nevertheless true that the same general principles apply to chain reactions both on earth and in the remainder of the universe ; in particular, large scale reactors can more readily give chain reactions than can smaller ones.

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## CHAPTER XI

# THE REALIZATION OF AN ATOMIC CHAIN REACTION

(1) *Administrative arrangements for atomic energy research.*

Before we consider some of the practical results which have arisen from the investigations into the possibility of releasing atomic energy, it is appropriate to mention the organizations which were set up in Great Britain and in the United States of America to determine the feasibility of making an atomic bomb, and to give some account of the problems which were investigated.

In Great Britain research work on nuclear fission and its use in an atomic bomb was carried out under a special division of the Department of Scientific and Industrial Research called the Directorate of Tube Alloys.* The supervision of this directorate was in the hands of Sir John Anderson and a consultative Council. In addition, under the chairmanship of the Director there was a technical committee on which served a number of distinguished British physicists who had great experience in nuclear investigations.

Some details of the British work are mentioned later, and at present it is only necessary to say that by the beginning of 1942 it was clear that the limited British resources available gave little prospect of producing an atomic bomb in this country. Early in 1943, one section of the experimental work, which till then had been carried out in Cambridge, was transferred to Canada, and towards the close of that year arrangements were made for the closest cooperation between the British and American work on the atomic bomb. About that time, and during the course of 1944, a considerable number of scientists engaged on Tube Alloys work in this country were moved to the U.S.A. where it was believed that they could contribute more to the war effort by helping with some of the problems which were arising in connection with the realization of the atomic bomb.

Although the U.S.A. did not enter the war until the end of 1941, from 1939 onwards there was an appreciation of the potential value of atomic fission in the production of a bomb, and early in 1940 arrangements were made for restricting publication of important papers on this subject. When the National Defense Research Committee was set up, an earlier government committee on uranium research was brought under its control, but up to the time of the American entry into the war, work was carried out on a relatively small scale. In the meantime, there had been some interchange of infor-

* Tube Alloys work was a code name for Uranium research work.

mation with the British, and towards the end of 1941 American physicists visited Great Britain in order to obtain first-hand knowledge of what had been done here. As a result of information obtained in Great Britain and of independent investigations by American scientists, it was felt that there was sufficient hope of achieving an atomic bomb to make it desirable to enlarge the scale of the work in the U.S.A. Plans to do this were announced to the Uranium Committee of the National Defense Research Committee a few days before Pearl Harbour. In accordance with these plans the responsibility for atomic energy research was transferred to the Office of Scientific Research and Development.

During the course of 1942, a special group of the American Army Corps of Engineers was formed to carry on work on atomic bombs, and in charge of this group, which was known as the Manhattan District Engineers, was General L. R. Groves. On 1st May, 1943, the Office of Scientific Research and Development transferred all parts of the atomic bomb project to the Manhattan District Engineers who remained in control of the work until the end of the war.

(2) *Requirements of the bomb and of the controlled release of atomic energy.*

Viewed in the most general way, the problem was that of determining the possibility of a chain reaction by the fission of uranium or of any other material which possessed the necessary properties and which was available in sufficient quantity. For use in a bomb it was necessary to have a chain reaction with a reproduction factor considerably greater than unity and to have circumstances in which a very short time elapsed between the occurrence of one fission and those resulting from the neutrons thereby released; in other words a high reproduction factor and a small reproduction time* were essential. But if, on the other hand, a chain reaction was to be used to yield useful energy from nuclear fission processes, it was necessary to devise a system in which the reproduction factor could be adjusted so as to have an average value of unity; furthermore, in this case, it was an advantage to arrange that the time of a generation was long, for in such circumstances no serious danger would arise if the reproduction factor rose temporarily above unity, provided, of course, reasonably prompt action was taken to diminish it. In view of the considerations outlined above, the research work divided itself into two general investigations; one directed towards achieving a fast-growing chain reaction such as was required in an atomic bomb, and the other for the realization of a large scale controllable chain reaction from

* The average time between consecutive fissions in a chain. This time is occasionally called the time of a generation (of neutrons).

which energy would be released because of the continuous consumption of the fissionable material.

Not only did these two lines of investigation have very different objects in view; they involved the use of fission on very different scales. For if we can realize the whole of the energy available, the fission of 1 lb. of uranium—yielding as much heat as is obtained on burning one thousand tons of coal—if carried out in a reasonably short interval of time will produce an explosive effect comparable with that arising from an ordinary bomb containing some thousands of tons of high explosive. Clearly, if it were found possible to construct an atomic bomb which used only a few pounds of fissionable material, and if the whole of the energy of this material were released in an explosive manner, the destructive effect would be on a very considerable scale. A few hundred pounds of this atomic explosive would produce enough bombs to convince an enemy of the futility of prolonging a war. And even if conditions were less favourable than we assume, a few successful atomic bombs, exploded so that the enemy was convinced of their effectiveness, were likely to have so great a psychological effect that the war would be brought to an end. However the matter was viewed it was clear that if a fast-growing fission reaction could be achieved, and if something like a ton of the necessary material could be produced, the means would be at hand to achieve immediate victory. Because only relatively small quantities of material were required, it was quite reasonable to contemplate the use of materials such as $U^{235}$, which were difficult and extremely costly to prepare.

The requirements of the controlled chain reaction were quite different. If such a reaction was to be used for large scale production of power, it was essential that the necessary materials should be available on a corresponding scale, for even if it proved possible to obtain by fission of one pound of uranium as much heat energy as is yielded on burning two million pounds of coal, it was clear that energy produced by such a process would be without great significance unless it involved the annual consumption, by fission, of one hundred tons of uranium. Such considerations made it desirable to examine the possibility of achieving a chain reaction depending on the use of natural uranium, and experiments to this end were carried out both in Great Britain and in the United States of America.

(3) *Plutonium: Mode of formation and properties.*

However, the interest in a controlled chain reaction did not arise solely because of the energy which it might be expected to release. Curiously enough, because $U^{238}$ captures slow neutrons without fission, the controlled chain reaction depending upon natural uranium was of the greatest importance

in connection with the achievement of an atomic bomb. The reasons for this are as follows. When $U^{238}$ captures a slow neutron it forms $U^{239}_{92}$, a radioactive substance which emits β rays and has a half life of 23 minutes. This material on β ray emission yields a nucleus of atomic number 93. The element of this atomic number has been named neptunium, and the particular nucleus formed in this case is $Np^{239}_{93}$. Now neptunium is a radioactive substance which emits β rays; its half period is 2.3 days. After β ray emission there is formed from it an element of atomic number 94; this is plutonium; in fact it is $Pu^{239}_{94}$. This isotope is radioactive too, emitting α particles and giving $U^{235}$; actually its half life is so long that from the point of view of present considerations it can be regarded as a stable substance. Neptunium and plutonium are both of scientific interest because they are trans-uranic elements, and because they have only recently been discovered, but in view of the short life of neptunium, it is unimportant compared with plutonium. The importance of plutonium arose because the theories of Bohr and Wheeler,[1] when applied to it, suggest that it is likely to be subject to fission upon bombardment by slow neutrons. It will be remembered that before fission can occur a certain amount of energy, denoted by $E_f$, must be communicated to a nucleus; on Bohr's theory $E_f$ depends on $\frac{Z^2}{A}$ and decreases as this quantity increases. Here we are interested in the energy necessary to give fission of the nucleus formed after plutonium has captured a neutron, that is of the nucleus $Pu^{240}$, for which $\frac{Z^2}{A}$ has the value of 36.8. On comparing this with the other values in Table 1 we see that for $Pu^{240}$, $E_f$ must be smaller than for any of the nuclei listed there; it is not unreasonable to expect that $E_f$ will have a value close to 4.5 MeV.* This low value of $E_f$ is exceptionally favourable, but it does not in itself ensure that plutonium will give fission on bombardment by slow neutrons; this will not happen unless the neutron binding energy of $Pu^{240}$ is greater than 4.5 MeV. Although all the neutron binding energies listed in Table 1 are in excess of 4.5 MeV, it is desirable to consider the matter somewhat further, in case $Pu^{240}$ has a small neutron binding energy. This element is, however, an example of a nucleus which contains an even number of protons and an even number of neutrons, as is obvious from its even mass number and atomic number; such nuclei are known to have abnormally high neutron binding energies,† as is seen in the

* Turner [2] states that $E_f$ for $Pu^{240}$ is about 4.0 MeV.

† This consideration of Bohr's theory shows that $U^{233}$ should give fission upon bombardment by thermal neutrons when $U^{234}$ is formed in an excited state. $U^{233}$ can be formed from thorium by reactions similar to those which produce $Pu^{239}$ from $U^{238}$. (See Turner [2] and [4]).

case of $U^{236}$, the only similar nucleus of those listed in Table 1. From analogy with this uranium nucleus, we might anticipate for $Pu^{240}$ a neutron binding energy of about 6.5 MeV and unless this estimate is greatly in error, we may have confidence in our conclusion that $Pu^{239}$ will exhibit fission when it is subjected to bombardment by slow neutrons. The particularly high value of the neutron binding energy, and the much lower value of $E_f$, make it appear that when $Pu^{239}$ captures a slow neutron fission is very likely. Furthermore, when this substance captures a fast neutron, there will of course be the rival possibilities of fission and of neutron emission; but in the light of Bohr's theories of these alternative processes, one would expect to find that of those $Pu^{239}$ nuclei which capture a fast neutron, the majority will give rise to fission; whatever the actual magnitudes involved, the fraction of plutonium fissions resulting from fast neutron capture is likely to be considerably greater than in the most favourable case already discussed, that of actino-uranium, $U^{235}$.

(4) *Chain reaction with natural uranium.*

Further discussion of plutonium is reserved for later chapters; its mention here is necessary in order to show why so much interest was taken, especially in America, in the controlled chain reaction. If such a reaction were achieved, it would yield large amounts of heat energy, and in addition it would slowly manufacture the new element, plutonium, which would be very convenient to use in atomic bombs. Nevertheless, the real problem was to achieve a chain reaction using natural uranium, a problem which we have already seen to be difficult because of the strong resonance absorption of neutrons by $U^{238}$. Essentially, the realization of any chain reaction, even that involved in lighting a coal fire, involves the same considerations; if the chain reaction is difficult to commence, every precaution must be taken to avoid loss of the essential product of the reaction on which its spread depends. When lighting a fire, as much heat as possible must be retained for communication to other parts of the combustible material. When trying to arrange for a uranium chain reaction, the ideal requirement is to consume neutrons only in the capture process which gives rise to fission. From this point of view, any other use of neutrons represents a loss. On the other hand, in the same way that a coal fire which is only just capable of maintaining itself is of little use for giving warmth, a hypothetical uranium chain reaction in which no neutrons are captured by $U^{238}$ nuclei will be of no use for the production of plutonium. Whatever the outcome of plutonium production from uranium, the first essential is to achieve a chain reaction which will sustain itself; it is safe to leave to the future the arrangements which will permit the maximum production of plutonium as well as the maintenance of the chain reaction.

And so the primary requirement was that of arranging to avoid capture of neutrons by $U^{238}$.

This problem was considered carefully both in Great Britain and in the U.S.A. and although rather different solutions were proposed, both depended upon the same mechanism and both were successful. Let us recall the details of the problem. The fission neutrons are emitted with considerable energy and some few cause fission of $U^{238}$ nuclei; but most of the neutrons have small chance of capture until they have lost most of their energy and then of course there is the greatest likelihood of capture by $U^{238}$ nuclei. If this is avoided there is a considerable chance of neutron capture by $U^{235}$ and the occurrence of fission. The chance of loss of neutrons by $U^{238}$ capture is greatest when the neutrons are gradually slowed down within a mass of uranium; this chance is considerably reduced by slowing the neutrons quickly in a medium which does not capture them. If it is arranged that most of the neutrons are ejected into such a medium, and if they stay there until they are reduced to thermal energies, there will be the best possible chance of their causing fission of $U^{235}$ nuclei. With a view to achieving this it was proposed that large masses of uranium, either in metallic form or as the oxide, should be assembled in some regular way so that a considerable distance separated each mass of uranium from the next; around this structure, which was known as a lattice of uranium, was a neutron reflector and within this, in the spaces between the uranium masses, was a suitable moderator to slow down the neutrons. It was believed that such an arrangement would operate as follows. From a single fission would arise two fast neutrons; from one of these there might result the fission of a $U^{238}$ nucleus, but much more likely they would leave the mass of uranium in which they were formed and lose their energy in making collisions with the atoms of the moderator. Before long the neutrons would attain thermal energies and would make frequent collisions with the moderator and move about in random directions. Eventually it was hoped that the neutrons would enter a mass of uranium and that one, and not too rarely two, would cause a further fission after being captured by a $U^{235}$ nucleus.

If this arrangement is to succeed a number of requirements must be met. The uranium masses should contain no neutron absorbing impurities and should be sufficiently small to give a reasonable chance of the escape of a neutron before it has lost much energy; the distances between the uranium masses should be such that a neutron has little chance of passing from one to another without being slowed down to thermal energies; the moderator should slow neutrons quickly and with the minimum of loss by capture. Finally, and in some ways this is the greatest difficulty, the structure must

be of sufficient magnitude to ensure that only a small fraction of the neutrons are lost by leaving the structure. It is here that the lattice structure, and the use of the moderator, have their most serious disadvantages. For a structure of given size, there is relatively little neutron-producing material—$U^{235}$—and much too much surface area from which neutrons can escape. To achieve the desired chain reaction a large structure containing a great deal of uranium will be required; furthermore, it is essential to arrange to keep avoidable neutron losses at the lowest possible level.

The first big problem is that of obtaining a suitable moderator. In order to slow the neutrons quickly and in the smallest possible path distance, the moderator must be a light element. Common hydrogen of mass unity is the first choice, for as we have already seen some neutrons lose their total energy as a result of a single collision with a hydrogen nucleus; but hydrogen has a capture cross section for slow neutrons which is too large to make it suitable. Other light elements are deuterium (heavy hydrogen), helium, lithium, boron, beryllium and carbon, but as carbon has a mass of 12 it is much less suitable for slowing down neutrons than is hydrogen or heavy hydrogen with masses of 1 and 2 respectively. Lithium and boron are both quite unsuitable because of their large capture cross sections for thermal neutrons,* so that there remain for consideration deuterium, helium, beryllium and carbon. Of these, helium can be ruled out at once, for although its ability to slow neutrons is entirely satisfactory, it is available only in gaseous form and consequently the average path traversed by a neutron in being slowed down, even in high pressure helium, is far too large to permit its use. Beryllium was not impossible as a moderator but as no more than 700 lb. of this metal was produced in the year 1940 in the U.S.A., it was considered that a major problem would arise if it was necessary to obtain sufficient quantities for use as a moderator in a controlled chain reaction. There remain, then, only heavy hydrogen and carbon.

In Great Britain, where this controlled chain reaction was carefully considered, circumstances favoured studies of the use of heavy water as a moderator. As has been told before,[3] just prior to the invasion of Norway, the French Government purchased from the Norsk Hydro Company 165 litres of heavy water. This heavy water, which represented almost the total world stock, was brought to Britain at the time of the fall of France in 1940. Drs. Halban and Kowarski, who brought it, had been instructed by Professor Joliot to attempt to carry out in Britain an experiment which had been planned in Paris and for which the heavy water had been acquired. Such an experiment was carried out in Cambridge, and as a result it appeared that it

* Compare Chapter VIII, p. 78

was possible to achieve a chain reaction if uranium oxide was used as the active material and heavy water was used as a moderator. It appeared further that if uranium metal was used in place of uranium oxide, the size of the reacting mass could be considerably decreased and that not more than a few tons of heavy water would be required for the construction of a workable system. To achieve this reaction in Britain during the war was hardly practicable, especially as a great effort would have been required to obtain adequate quantities of heavy water, which has to be extracted by tedious processes from ordinary water. For this reason the French physicists were transferred to Canada to continue there the investigations of chain reactions using heavy water as a moderator.

(5) *Supply of materials for uranium chain reaction with carbon moderator.*

In the U.S.A. the possibility of using heavy water as a moderator was also considered, but in view of the necessity for providing much more heavy water than was available or could be produced within a short period of time, it was decided to attempt to make use of graphite. This material was one which was already in large scale production, but this did not mean that the necessary supplies were available ; for not only was there a heavy demand for the available graphite, but the material being produced was of doubtful usefulness because, when a beam of slow neutrons was passed through it, many of the neutrons were absorbed. The graphite problem was thus mainly one of purity, although priorities were also involved ; these difficulties were satisfactorily overcome, and by the middle of 1942 large orders for graphite had been placed with the manufacturers.

In the meantime serious difficulties had arisen in connection with the necessary supplies of uranium metal. At the end of 1941 the only pure uranium metal in America was a few grams made on an experimental basis by the Westinghouse Electric and Manufacturing Company and others ; in addition there were a few pounds of metal containing much impurity. As a raw material there was available a commerical grade of black uranium oxide which contained 2%—5% impurity and which was found experimentally to absorb neutrons too strongly to make possible a chain reaction. Again, the problems were solved, and by May 1942 black uranium oxide of reasonably high purity was being delivered at the rate of 15 tons a month ; at about the same time arrangements were completed for converting this material into very pure brown uranium dioxide ; in July 1942 this material was being delivered at the rate of 30 tons a month.

The pure uranium metal as produced by Westinghouse had been prepared by an electrolytic process at the cost of $1000 a pound. New methods of

preparation were developed, and by the end of 1942 deliveries had exceeded 6000 lb. and were rising to more than half a ton a day. The purity of some of the metal was good, and its cost had fallen to $22 a pound. Although for some time the metal was rather less pure than was desired, more satisfactory methods were developed, and by the middle of 1943 new plants were in operation and were delivering uranium which satisfied requirements.

(6) *Tests of materials for uranium-carbon pile.*

In the meantime, of course, the necessary materials were not available to make possible an experimental test of a chain reaction and in consequence those who were responsible for the design of a reacting mass to give a controlled chain reaction—such a mass is usually known as a pile—decided to carry out experiments from which they could predict the reproduction factor of a pile built from given materials. It is well to recall that a pile will not give a chain reaction unless the reproduction factor is greater than unity, and that this failure may arise either because too large a fraction of the neutrons escapes from the surface of the pile or because the materials or their disposition in the pile, or both, are unsuited to the development of a chain reaction. In the former case, a sufficiently large pile will develop a chain reaction, but in the latter case an increase in the size of the pile will not cause it to operate ; for even in the centre of such a pile, from which no neutrons are lost by emission from the surface, the neutrons from one fission are not, on the average, able to produce a further one. In this connection it is useful to distinguish two reproduction factors, one $k_\infty$, the reproduction factor for a pile of given arrangement and of infinitely large size—where a negligible fraction of the neutrons is lost at the surface—and k, the reproduction factor for the given pile of finite size. In terms of these quantities, no pile will operate unless k is at least unity ; if $k_\infty$ is greater than unity, a big enough pile will have a reproduction factor of unity and will give a chain reaction. When testing the suitability of materials for use in pile, one must first determine whether they are capable of giving a reproduction factor greater than unity for a pile of infinite size, that is one must measure $k_\infty$ to determine whether it exceeds unity ; unless it does, no purpose is served by building a pile.

During the course of 1942, experiments were designed and carried out to determine whether it was possible to arrange a lattice of lumps of uranium oxide in a mass of graphite in such a way that $k_\infty$ was greater than unity. The experiments involved the construction of a small pile in which a proposed disposition of uranium and graphite was employed ; below the pile was placed a source of neutrons, and measurements were made of the number of

neutrons inside the pile at different distances from the source; from a knowledge of the way in which the number of neutrons would be expected to decrease with increasing distance from the source, and of the influence on this of the absorption and release of neutrons in the materials of the pile, it was possible to determine $k_\infty$ for given materials and arrangement. The influence of purity of materials was paramount, as was known from an experiment which had been carried out a year earlier. On that occasion a graphite cube with a volume of about 500 cub. ft. had been built; within it some 7 tons of uranium oxide in iron containers was distributed throughout the mass. The materials were not in a very pure state and the lattice arrangement was probably not the optimum, so that there were reasons for supposing that the performance indicated by this early experimental pile was considerably below what could be achieved; but the measurements showed then that success was far off, for $k_\infty$ was no more than 0.87. However large a pile was made with those materials in the lattice form actually tried, no more than 87 neutrons would be produced for every hundred introduced into the pile; the possibility of achieving a chain reaction had not at that time been shown.

In 1942 the materials available were much purer, and careful experiments showed that with them a value of $k_\infty$ of 1.007 could be achieved. The importance of this result can hardly be overestimated, for it showed beyond doubt that a neutron chain reaction was possible. The size of a successful pile cannot immediately be deduced from $k_\infty$, but this can be determined when additional data are available concerning neutron losses at the boundary of the pile. The experiments showed that a self sustaining pile was large but of practicable size if it employed the materials and arrangements which had been tested.

(7) *Method of control of the pile.*

These experiments showed that a pile could be made in which the release of atomic energy would occur. How was this energy release to be controlled? This matter was a very serious one for it was clear that considerable damage would result from a pile which went out of control. As already mentioned, the fission process occurs within a very short time after the moment at which the neutron is captured by a uranium nucleus, and the fission process is associated with the simultaneous emission of neutrons. Most of these neutrons pass into the moderator where they proceed to lose energy at such a rate that half of it is lost in four collisions with the carbon atoms in a graphite moderator; after about one hundred collisions, an average neutron of 1 MeV initial energy is reduced to thermal energies corresponding to 0.035 eV. Such a neutron will have a velocity of about 2000 metres per sec. and on the average

it will make a further hundred collisions and move a distance of 2.5 metres before it passes back into the uranium. When the neutron is fast, the collision cross section of the carbon atoms will be small so that the neutron moves considerable distances between collisions; but as it moves at high speed we do not make a great error by assuming that the average time between collisions is much the same whatever the speed of the neutron. On this basis, no more than $2.5 \times 10^{-3}$ sec. elapses between one fission and the fission produced by the neutrons it releases.

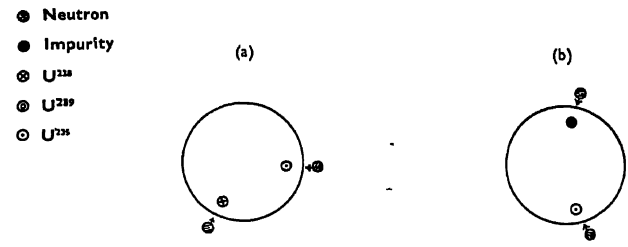
If, then, a pile is made with a reproduction factor of, say, 1.003, and the period between successive neutron generations is $2.5 \times 10^{-3}$ sec., one million fissions at one moment will grow, in a second, to 3.3 million fissions, and unless some action is taken the fission process will continue to increase at this rate. A pile will operate at constant level only if the reproduction factor is exactly unity; if it is lower than this value, the neutron density and the reaction rate will diminish, but if it is higher than unity, the reaction rate will increase until it brings about such a disturbance of the conditions in the pile that the reaction rate becomes steady. Naturally, it is likely to be difficult to maintain the reproduction factor at the desired value of unity, and as it turns out this is not necessary; satisfactory operation will occur if k is held very slightly above unity until a predetermined increase of reaction rate has occurred, when it can be reduced to a value at which the reaction rate slowly diminishes. When this diminution has proceeded sufficiently, the value of k can be increased and this cycle of fluctuations can be repeated indefinitely. Such an arrangement is quite practicable. The overall value of k for a pile can readily be reduced by introducing into the pile a substance like cadmium which strongly absorbs slow neutrons. Automatic means can be provided to move absorbing strips of cadmium-containing material, or of boron steel, in or out of the pile according as the rate of reaction is above or below its desired value. Our calculation of the time between successive generations of fissions suggests that this control mechanism should operate rapidly, but fortunately this is not necessary for not all the neutrons are emitted at the moment of fission; the existence of the delayed neutrons plays its part in making a pile easy to control. We can understand this by regarding the reproduction factor as arising in part from the neutrons emitted at the instant of fission and in part from the delayed neutrons; if we arrange that the first portion is made just less than unity and that the sum of the two exceeds unity, the build up of the chain process will then depend on the release of the delayed neutrons and will occur quite gradually. It is still necessary to move absorbing strips to positions where k is very close to unity, but even if this adjustment is made slowly, very satisfactory control of the chain reaction can be achieved.

(8) *The first successful uranium chain reaction.*

When a pile is built, provision must be made for the introduction into the pile of the rods that control the reproduction factor; furthermore, as a precaution, it is desirable to make tests to determine the reproduction factor of the pile at a number of stages in its construction. From these tests it is possible to estimate the size of the pile at which the reproduction factor will just attain the value of unity. It will be appreciated that even though this factor is less than unity, any neutron within the pile will be almost certain to give rise to further neutrons. This chain of reactions does not maintain itself, but it is easy to show that if the reproduction factor is $k$, and is less than unity, each neutron will, on the average, produce a further $\frac{k}{(1-k)}$ neutrons. If a source of neutrons is used, this phenomenon enables a determination to be made of the reproduction factor even though it is less than unity.

The first reacting pile was erected in the autumn of 1942. By this time some uranium metal was available and nearly six tons was included, although apparently the bulk of the uranium was in the form of lumps of pressed uranium oxide. This pile was known as the West Stands pile and was originally built in the grounds of the University of Chicago. It was planned to build the pile in a form which was approximately spherical, but in fact the critical size—that at which the reproduction factor became unity—was reached before the sphere was complete and the shape of the pile was somewhat modified; when all the neutron absorbers were removed from the pile the reproduction factor was found to be about 1.0006. This pile first operated on 2nd December, 1942, when it liberated atomic energy at the rate of 0.5 watt, a power yield which is so small that it produced a negligible heating of the material of the pile. The energy liberated was in fact calculated in terms of the neutrons which were produced in the pile; these amounted to about $3 \times 10^{10}$ per second, corresponding to some 10 neutrons per second per cubic centimetre of material of the pile. Ten days later the rate of energy release was increased to 200 watts; this figure was not exceeded because it was felt that to raise further the power output would produce radiations of such intensity as to endanger people working in the neighbourhood of the pile.

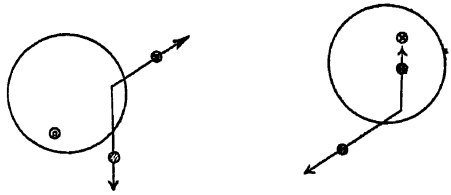
Thus by the end of 1942 it was proved that the slow neutron chain reaction was feasible and that atomic energy could be released from uranium. There was little doubt that the uranium chain reaction could be carried out on a much larger scale, when perhaps it could release energy in vast quantities. Perhaps a larger pile could be used to produce plutonium in considerable amounts. It will be realized that the operation of a pile involves the occur-

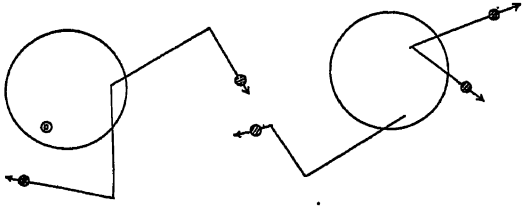



(a) and (b) : Two slow neutrons about to enter each lump of uranium.

(a) : One neutron has been captured by a $U^{238}$ nucleus and a $U^{239}$ nucleus results. The other neutron gives fission with a $U^{235}$ nucleus.

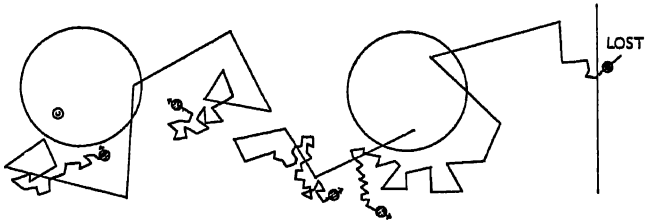
(b) : One neutron is captured by an impurity. The other gives fission.





(a) : Fission neutrons make elastic collisions with nuclei of the moderator.

(b) : One of the fission neutrons gives fission with a $U^{238}$ nucleus.




(a) and (b) : The fission neutrons make frequent collisions with the moderator. One is lost. Of the four remaining one is about to enter a lump of uranium.
Two lumps of uranium (a) and (b), in a carbon moderator.

**Fig. 31.** Some processes in a slow neutron chain reacting pile.

rence of a number of different nuclear reactions, some of which are shown in Fig. 31; the successful achievement of a controlled chain reacting pile is evidence for the correctness of our ideas about the nuclear processes occurring within it.

(9) *The Clinton pile at Oak Ridge, Tennessee.*

The next problem was that of devising a uranium-carbon pile which would liberate energy at a much greater rate, for only by actual experience could information be obtained concerning a number of doubtful points; in addition such a pile could be expected to give considerable information about the possibility of preparing plutonium on a large scale. It was therefore decided to construct a uranium-carbon pile near Clinton, Tennessee; this pile was to be air cooled and was designed to be capable of liberating atomic power at the rate of 1000 kW. Although this pile was originally intended as a pilot plant for some much greater piles which were being designed, it did not in fact serve this purpose, but it did provide information on problems relating to the control of a pile and, much more important, it gave essential experience in the handling of plutonium.

The Clinton pile was cubical in shape and used a graphite moderator; within the graphite mass were horizontal channels in which were placed gas-tight aluminium cans containing cylinders, or "slugs," of uranium metal. Sufficient space was available to permit adequate flow of cooling air past the aluminium cans, and arrangements were made by which they could be pushed out of the pile when this was desired. The pile was of course provided with additional channels for the control rods and for various instruments which were used to make measurements of the operating characteristics of the pile.

This pile was put into operation on 4th November, 1943, and within a few days of this time the power liberation was brought up to 500 kW, in which condition the surface of the uranium slug containers reached 110°C. Improvements in the air cooling system allowed the power level to be raised to 800 kW, although this involved a can temperature of 150°C. As a result of further improvements, including a redistribution of the uranium and improved techniques for sealing the aluminium cans which contained the slugs, it was possible to operate the pile at power levels in excess of 1800 kW, the figure attained in May of 1944. By this time the pile was liberating nearly twice the energy for which it was designed, and generally its performance exceeded expectations. It was easy to run, it was steady in operation, and it could be controlled without risk to the operators. The pile was provided with numerous measuring instruments and safety devices and was to all appearances a very complicated piece of mechanism. In fact, however, its most striking

feature was simplicity of operation; most of the time the operators had nothing more to do than to record the readings of the indicating meters.

(10) *Preparation of heavy water for uranium-heavy water pile.*

It is appropriate to conclude this chapter by describing the work that was carried out in connection with a pile using heavy water as a moderator. We have already seen that heavy water is a better moderator than carbon, if only because, on the average, more energy is lost when a neutron collides with a deuterium atom than when it collides with a carbon atom. This advantage is somewhat reduced because 5 cm.$^3$ of carbon contains as many atoms as 9 cm.$^3$ of heavy water, but it remains true that heavy water slows the neutrons more quickly than does carbon in the form of graphite. Furthermore, as heavy water has a smaller capture cross section for slow neutrons than graphite, there is an additional advantage in using it. The main reason for using graphite in the American experiments was the absence of any considerable supply of heavy water; the decision to use graphite involved the risk that a pile depending upon it might fail to operate, and for this reason the work of preparing large quantities of heavy water was undertaken.

Two methods of preparation were used. The first and simplest was the fractional distillation of water. The separation produced by this method depends on the fact that the boiling point of heavy water is somewhat different from that of ordinary water; when water is distilled the steam which first comes off is somewhat poorer in heavy water than are later fractions. Unfortunately the boiling points are so close together—the boiling point of heavy water is only 1.4°C. higher than that of water—that a great deal of water must be boiled in order to concentrate appreciable quantities of heavy water, and although this method was successful and required only simple and well understood equipment, it was wasteful.

The second method of preparation depended upon the exchange of deuterium between hydrogen gas and steam or water in the presence of a catalyst. When equilibrium is established the concentration of the deuterium in the water is greater than in the gas by a factor of about three. In principle, hydrogen is mixed with steam, passed over beds of catalyst and then bubbled through down-flowing water. Part of the deuterium originally in the hydrogen exchanges with hydrogen in the steam and increases the deuterium content of the steam; the steam is then absorbed in the down-flowing water which is subsequently electrolysed so that the hydrogen may be used again in a continuous process. The scheme involves the handling and rehandling of immense quantities of material, but despite this the process was found to be economical in operation. A plant using this method for preparing heavy

water was set up in Trail, British Columbia, Canada, this site being chosen because of the necessity for having available large amounts of electric power for the electrolytic preparation of hydrogen.

(11) *Performance of uranium-heavy water pile.*

Eventually, then, during 1944, a uranium pile with heavy water as a moderator was built at the Argonne Laboratory outside Chicago; by 15th May this was ready for testing. When all the uranium was in place, the moderator was gradually added and all the time measurements were made of neutron intensities in order to determine the moment at which the reproduction factor attained the value of unity. No real difficulty or danger was anticipated, for of course the usual safety arrangements were provided, and rods of neutron absorbers were so placed as to be readily inserted into the pile. The pile as designed was small compared with a uranium-carbon pile, but the designers were astonished to find that, by the time three-fifths of the estimated requirement of heavy water had been added, a chain reaction commenced. Had the total quantity of heavy water been added at one time, the value of k would have been appreciably greater than unity and the neutron absorbing rods, even when fully inserted into the pile, would not have brought the reproduction factor to a safe value. But when only a portion of the moderator had been added, and the chain reaction commenced, these rods had sufficient influence to enable the reaction to be stopped. Subsequently some of the uranium was removed from the pile, extra neuron absorbing control rods were inserted and the calculated amount of heavy water moderator was added. The pile operated satisfactorily and on 8th August, 1944, it was developing about 300 kW of power, all of which came from nuclear reactions occurring in the pile.

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## CHAPTER XII

# THE PRODUCTION OF PLUTONIUM

(1) *Discovery and preparation of first small supplies.*

The possible importance of plutonium was discussed in the previous chapter where it was explained that this substance resulted from two short period radioactive processes occurring after a radiative neutron capture by $U^{238}$. It was apparent, however, that plutonium would be used in atomic bombs only if it were prepared in relatively large quantities, and to achieve this required an effort of great magnitude. The belief that plutonium was suitable for atomic bombs arose initially from Bohr's theories and from a general consideration of the precise masses of the elements, particularly of the radioactive elements; initially there was no direct evidence to support the prediction that plutonium, like $U^{235}$, was subject to fission on bombardment by slow neutrons; there was not even an appreciable quantity of plutonium in existence.

Plutonium was first discovered as $Pu^{238}$, a rather short-lived radioactive substance which on emitting $\alpha$ rays becomes uranium II ($U^{234}$). The discovery was made in the following circumstances. A cyclotron in the Radiation Laboratory of the University of California at Berkeley was used to bombard uranium with fast deuterons. From the bombarded uranium neptunium, $Np^{238}$, was separated, the first true trans-uranic element to be isolated.* Early experiments showed that $Np^{238}$ emitted $\beta$ rays, but the nature of the product substance was not then determined. Subsequently, when larger quantities of $Np^{238}$ had been prepared, the methods of tracer chemistry† were employed to determine the chemical properties of the substance produced by radioactive decay of $Np^{238}$, an element which we now call plutonium, the isotope formed being $Pu^{238}$.

In the summer of 1940, the nuclear physics group at Berkeley was urged to use the neutrons produced by bombarding deuterium with deuterons from its cyclotron for the purpose of producing $Pu^{239}$, with a view to separating it from uranium and determining its fission properties. The mode of formation of this isotope, by two $\beta$ ray emissions following radiative capture of a neutron by $U^{238}$, has already been discussed, but although the likelihood of such a reaction was widely accepted, it was not verified until late in 1940. In 1941, Lawrence, of the University of California, reported that experiments in

* The reaction is $U_{92}^{238} + H_1^2 = Np_{93}^{238} + 2n_0^1$.

† See Appendix II.

Berkeley had indicated that plutonium was formed in the manner we have described and that it underwent fission when it was bombarded by slow neutrons. Lawrence pointed out that a controlled chain reaction with natural uranium might be used for the production of plutonium, that this substance could probably be separated from uranium by ordinary chemical methods, and that it might then replace $U^{235}$ as a possible fissionable material for use in an atomic bomb.

By the end of 1941, when more information was available concerning plutonium, it had been ascertained by using the methods of tracer chemistry that satisfactory processes could probably be devised for separating plutonium from uranium. There was little doubt about the general soundness of the proposals to manufacture plutonium, but there was much uncertainty on a number of specific points and in particular on matters relating to the adequacy of the proposed methods of chemical separation. To settle some of these doubts, cyclotrons in Berkeley and in St. Louis were used for the production of plutonium. Although several hundred pounds of uranium salt was subjected to neutron bombardment, it was not until the end of 1942 that the product was available in sufficient quantity ; the yield consisted of 0.5 mg. of plutonium—less than would be needed to make the head of a pin. Small as was this amount of material, it was enough to permit microchemical methods to furnish much reliable information about the chemistry of plutonium.

On this subject few details are available ; from the position of element 94 in the atomic table, plutonium might be expected to be similar to the rare earths or to uranium, thorium or osmium.[1] According to the Smyth report, from which the information in this paragraph is taken, plutonium is more like uranium than any of the other elements named and it may be regarded as a member of a new rare earth group which commences with uranium. However this may be, by the end of 1942, plutonium, which was not known prior to 1940, and even then was available only in microscopic amounts, was an element whose main chemical and physical properties were well established.

(2) *Possibility of large scale production of plutonium.*

And yet the feasibility of using chain reactions to prepare large amounts of plutonium was at the end of 1942 subject to doubt. At this time, it will be remembered, the first pile—the West Stands pile—had operated. This pile gave little help in laying doubts to rest, for although it did work, the uranium was arranged in a way which was very favourable for achieving a chain reaction but which was quite unfavourable for permitting the extraction of plutonium. It was essential to arrange the uranium so that it could readily

be removed from the pile, and for this reason it was proposed to build the mass of carbon moderator so that it contained longitudinal holes into which the uranium could be placed, as has been described in the last chapter; such an arrangement made it easily possible to push portions of the uranium out of the pile, but as it was less favourable than that used in the West Stands pile from the point of view of the development of a chain reaction, there was some doubt as to whether such a pile would work. Subsequent analysis and experiment showed that it was possible to construct a pile which would work and permit the removal of uranium for the extraction of the plutonium in it, and these conclusions were verified by the operation of the Clinton pile at Oak Ridge during the winter of 1943-44. But even when it was realized that a suitable pile could be devised, a number of outstanding problems remained.

These included the following questions. How much power will be released by a pile which manufactures plutonium at the rate of 1kg. per day, and how is this power to be removed ? How much radiation is emitted, how dangerous is this radiation and how can the operation of a pile be made safe for the necessary personnel ? What dangers have to be anticipated from the chemical processes involved in handling the uranium that has taken part in a chain reaction and how can the necessary chemical processes be carried out without danger to the operators ? In addition there was the necessity of testing and improving the proposed chemical processes and of finding experimentally the materials which were able to exist, without deterioration, in the intense streams of radiation which arise within an operating pile.

(3) *Yield of heat and plutonium.*

Let us examine these problems; we commence by considering some of the characteristics of a pile which is capable of producing 1 g. of plutonium per day. The size of the pile must be large enough to allow a chain reaction to occur but not so large that the removal of the heat generated in the uranium becomes a major problem. Linear dimensions are kept a close secret and as they depend on the purity of available materials as well as on their actual arrangement, it is not very profitable to speculate about them. It is useful, however, to determine the order of magnitude of the energy liberated during the production of 1 g. of plutonium. Since the atomic weight of plutonium is 239, 1 g. will contain about $2.5 \times 10^{21}$ atoms and its production will require the liberation of $2.5 \times 10^{21}$ neutrons for resonance capture by $U^{238}$, a requirement that is approximately met by $2.5 \times 10^{21}$ fissions, each releasing two neutrons and about 200 MeV. Hence these fissions liberate about $5 \times 10^{23}$ MeV or in terms of larger units about 24 000 kWh, and to produce 1 g. of plutonium a day a pile will liberate power at the rate of 1000 kW. If we are more ambitious, and wish to provide for the production of 1 kg. of plutonium

a day, we must arrange to remove heat from the pile at the rate of about 1 million kilowatts. These figures are surprising; they serve to show that even though we have discovered the means of transmuting elements the processes are difficult, for they involve the liberation of heat on a scale that far transcends that produced in ordinary chemical processes. It may be possible to manufacture plutonium at the rate of 1 kg. a day, but if so a very large and elaborate plant is required.

(4) *Cooling the pile.*

To remove heat energy amounting to a million kW is an undertaking of some magnitude in the simplest of circumstances but in a pile circumstances are not simple. In order to avoid the use of piles of undue size, it was necessary to operate with higher neutron densities and to employ more effective cooling than had been used with the Clinton pile, and air cooling was not considered to be adequate. It will be remembered that almost all the heat is developed in the uranium whence it must be withdrawn without absorbing an unduly large number of neutrons. The uranium then must be in good contact with an efficient cooling fluid of such a nature that few neutrons are captured by it. There are not many fluids which are at all suitable; helium, water and molten bismuth were all considered, and for a time it was intended to use helium cooling, but finally water cooling was decided upon and this was successfully employed.

The problems of cooling the pile were not of course immediately solved when the decision to use water cooling had been reached. It was necessary to provide a large flow of water, the actual amount depending upon the rise in water temperature which was allowable; when it is remembered that with a temperature rise of 60°C. a water flow of 4 tons of clean water a second is needed to remove heat energy at a rate of 1 million kW, it can be seen that very extensive water purifying and circulating systems were required. It was originally intended to erect the large production piles at Oak Ridge, but subsequently it was felt that even this part of Tennessee was not sufficiently isolated from centres of population, and finally an area of about 1000 square miles was acquired on the Columbia River near Pasco in Washington State. The situation of this region, the absence of nearby centres of population, the availability of cool, pure water supplies from the Columbia River, and the possibility of drawing large amounts of electric power from the Grand Coulee Dam, about 140 miles to the north, made the Hanford site a favourable one. It was necessary to provide water pumping plant on a scale such as is required for a fair sized city, a need that was met by engineering along well established lines. It was also essential to ensure that any water returned to the Columbia River was free from appreciable radioactivity arising from its passage through

a pile, but this was not difficult to arrange; and calculation showed that the operation of the projected piles at Hanford would not raise the temperature of the Columbia River by an important amount so that in no possible way could these piles have any effect on the fish life of the river.

(5) *Canning*: *The problem of a jacket to prevent corrosion of the uranium slugs.*

Although these aspects of the removal of the heat from the pile presented a task of considerable magnitude, the problems involved were straightforward compared with those of arranging satisfactorily to remove the heat from the uranium in which it was chiefly produced. Now hot water attacks uranium and so the proposal was to enclose the uranium in a sealed jacket which would prevent corrosion by the cooling water and would also ensure that the fission products released in the uranium were retained within the jacket. In view of the large amounts of heat which were to be liberated within the uranium, it was essential to ensure good thermal contact between the uranium and the protective can; furthermore, the only available materials which could be considered for jackets were those which imposed little restriction on the free passage of neutrons. The various requirements are satisfactorily met by an aluminium can, provided that it is arranged that good thermal contact is made between it and the uranium. This condition, and that of ensuring that the can was gas tight during the period it was in the pile, were very troublesome to satisfy, and yet the provision of absolutely reliable cans was essential if the pile was to operate safely and continuously. Apparently the solution of this problem—known as the canning problem—was in doubt until a very short time before it was necessary to load the uranium into the first Hanford pile, and in fact a minor modification of the method of canning was necessary after this pile had commenced operation. Despite the difficulties and uncertainties which were associated with this problem, the methods used proved satisfactory, and up to the summer of 1945 no can failure had been reported.

(6) *Radiations from a pile.*

The next problem to consider is the effect of the radiations produced by the pile. It will be remembered that uranium and plutonium are both radioactive substances emitting $\alpha$ rays, that $U^{239}$ and $Np^{239}$ are both $\beta$ ray emitters, and that the fission products emit $\beta$ rays and in some cases $\gamma$ rays as well; furthermore, the fission process results in the emission of neutrons which maintain the operation of the pile. There is little need to consider the effects of the $\alpha$ and $\beta$ particles at any point outside the pile; their paths in dense materials are so short that they are easily confined to the interior of the pile. Ideally, of course, no neutrons should be allowed to escape from the pile,

but despite the use of a carbon reflector around the pile, this ideal cannot be achieved and a pile in operation emits a very considerable number of neutrons in a second. The $\gamma$ rays emitted, either in the fission process itself, or after the emission of $\beta$ rays by the fission products, are of no benefit to the operation of the pile, but they too are likely to make their presence felt outside the pile. It is desirable to estimate the magnitude of the radiations escaping from the pile, for otherwise it will be impossible to prescribe adequate screens to protect those who are to operate it.

When we attempt to calculate the rate of emission of $\gamma$ rays or of neutrons from an operating pile, we are faced with a number of difficulties, of which only one is the lack of published information. If we consider a pile producing 1 g. of plutonium a day—and this of course must be regarded as a small yield—we see that there occur within it about $3 \times 10^{16}$ fissions per second; as a result of each fission there are about 10 $\beta$ ray transformations and it is not unreasonable to guess that each fission yields high energy $\gamma$ rays, which will be able to penetrate considerable thicknesses of matter, and which will produce ionization comparable with that produced by the $\gamma$ rays from the disintegration of 1 atom of radium and its products. Of the neutrons formed per fission only a small fraction will escape, but as the physiological effect of one neutron is considerably more serious than that produced by the penetrating $\gamma$ rays from one radioactive emission process, it may be assumed that the radiation per fission is equivalent to the $\gamma$ rays from 2 atoms of radium. Thus in every second the pile produces radiation comparable with that arising from the decay of $5 \times 10^{16}$ radium atoms; some part of this radiation is absorbed in the pile itself. In order to appreciate the seriousness of its effects we compare it with the radiation produced by 1 g. of radium and its short-lived products. Here we have occurring about $4 \times 10^{10}$ disintegrations per second, so that, on this basis, the pile previously discussed, which evolved heat at the rate of about 1000kW, will produce radiation which is of the same order of magnitude as the $\gamma$ rays from 1 ton of radium.

Now it is considered that the human body can tolerate for an indefinite period a daily dose of X radiation or of $\gamma$ radiation which produces $2 \times 10^8$ ion pairs in a volume of 1 cm.$^3$ of air. The amount of radiation which produces $2 \times 10^9$ ion pairs in 1 cm.$^3$ of air is known as the Röntgen unit, and is written as the "r unit"; the statement above is therefore equivalent to saying that a human being can tolerate a daily dose of radiation of 0.1 r unit. Isolated doses of larger amounts of radiation can be tolerated, but a dose of about 500 r units, given in a short time, is almost certainly fatal.

At a distance of 1 metre the $\gamma$ rays from 1 g. of radium produce about $4 \times 10^5$ ion pairs per cm.$^3$ per sec., so that a man could work safely at this

distance from 1 g. of radium for only about 8 minutes a day, whereas if he kept at a distance of 3 metres from the radium, he could safely work there for an hour and a quarter a day. The radium may be surrounded by some material which absorbs $\gamma$ rays ; it will then be safe for a worker to remain for a longer period in its vicinity ; but as ten inches or so of concrete is required to reduce the $\gamma$ rays to 0.1 of their original intensity, it is obvious that considerable amounts of such material are required to give adequate protection from large sources of $\gamma$ rays.

Returning to the consideration of the pile, we see, first of all, that a pile liberating 1 watt emits $\gamma$ rays and neutrons which are comparable in effect with the penetrating radiation arising from 1 g. of radium. Furthermore, if absorbing material is relied upon to reduce the intensity of the radiations from an operating pile, this material must be chosen to absorb neutrons and $\gamma$ rays. The figures given above show that the intense radiations from a pile liberating 1000kW will be capable of giving dangerous intensities after passing through a number of feet of concrete, a material which absorbs both neutrons and $\gamma$ rays. In fact, if a large pile is to be safe in operation it is best buried as completely as possible ; exposed parts should be completely enclosed in a thick layer of concrete and all operations should be carried out by remote control in such a way that no workers are at any time near the pile when it is emitting radiations. Naturally the whole of the pile cannot be enclosed in thick permanent shields ; arrangements must be made for the introduction and the removal of the uranium. This necessitates shields that can be removed, and these shields, as well as being sufficiently massive to provide adequate reduction of radiation intensity, must also be equipped to permit the flow of cooling water into the pile and at the same time must be air tight so as to prevent the escape from the pile of air which has been made radioactive by neutron capture processes.

(7) *Effects of radiation on materials within the pile.*

It must be remembered that any material within a pile is exposed to the full strength of these very intense radiations which we have been discussing, and it is natural to expect that they may eventually cause the deterioration or even failure of materials which are quite stable under the other conditions existing in the pile. This difficulty arises frequently in the engineering of a pile. The pipes carrying the cooling water in the pile must capture very few of the neutrons passing through them and they must not fail because of extended periods of irradiation by neutrons or $\gamma$ rays ; they must be good pipes and so they must not leak, warp or corrode. As it turned out, aluminium pipes were satisfactory, but uncertainty on this point only disappeared after they

had been successfully used in an operating pile. Again, these problems arise when making a choice of an electrical insulator to be used in the pile; such insulators are needed for various probes which are placed there and which convey information to the operators or to automatic controls which keep the pile working at a constant output level. Where the need for reliability and freedom from deterioration is great, almost any trouble is warranted if it leads to the discovery of a material which is really suited to the purpose being considered. Although the effects of prolonged neutron bombardment may be serious, there are not in fact a great many neutrons at any one time in unit volume of the pile. If we consider the case of a pile liberating 1000 kW of power, there are within it about $3 \times 10^{16}$ fissions a second, each of which gives two neutrons; as these neutrons have an existence of only about 0.0025 sec., there are only $10^{14}$ neutrons in the pile at one time and the actual number per cm.$^3$ must lie between $10^4$ and $10^7$. Lest this number should sound large, it is to be remembered that in what is regarded as a very good vacuum there are about $10^{10}$ atoms per cm.$^3$; the effects produced by the neutrons arise then, from their ability to interact with the matter through which they pass, rather than because there are so many neutrons present. In the course of time, incessant neutron bombardment is able to bring about changes in the physical—as distinct from nuclear—properties of materials. It is reported, for example, that the electrical resistance, the elasticity and heat conductivity of graphite are all changed by prolonged neutron bombardment.

(8) *The operation of a pile.*

In order to see what is the state of the uranium slugs when they are withdrawn from the pile after a prolonged period of operation, it is useful to follow briefly the chain of events that occurs when a pile is first put into operation. We can imagine the uranium slugs to be in place and the control rods to be slowly withdrawn so as to permit the starting up of the pile. The initiation of a chain reaction might be carried out by having a neutron source within the pile, but in practice it commences spontaneously either upon the arrival of a stray neutron, of which there are about 6 per hour falling on every cm.$^2$ of the outside of the pile, or from the spontaneous fission of a $U^{235}$ nucleus within the pile.[2] The chain reaction will build up relatively slowly, at a rate which depends on the reproduction constant of the pile and on the life time of a generation of neutrons. During the operation of the pile $U^{239}$ will be formed, but as this is a short-lived radioactive substance it will never exist in any quantity; in a matter of a few hours the amount present will reach its equilibrium value so that after this it will decay to $Np^{239}$ just as rapidly as it is formed. In a similar way the quantity of neptunium will build up to an equilibrium value which is more than 100 times that of the

equilibrium amount of $U^{239}$ and after a week or two, when this state has been reached, the rates of formation of $U^{239}$, of $Np^{239}$ and of plutonium will all be equal. $Pu^{239}$ is a substance of such slow decay that it will continue to accumulate in the uranium at a steady rate during the period it is kept in the operating pile. In addition to these reactions there occur the rather rare fissions of $U^{238}$ nuclei after the capture of fast neutrons, and the much more frequent fissions of $U^{236}$ nuclei formed by neutron capture from $U^{235}$. From these processes there arises the great variety of radioactive fission products, and eventually these materials reach equilibrium values in which the rate of production of any one of them is just equal to the rate of its decay.* For fission products which are derived from a common fission nucleus, the equilibrium amounts will be proportional to their half lives, so that there will be only small amounts of the short-lived fission products and much larger amounts of the long-lived ones. When a piece of uranium is within the pile, it becomes permeated with a variety of materials, most of which are radioactive; the main part of the radiations arising within this uranium comes from the fission products, although there are also appreciable contributions from the presence of $U^{239}$ and $Np^{239}$.

(9) *Extraction of plutonium.*

Immediately the uranium slug is removed from the pile, the radioactive substances will commence to decrease in amount and in the case of some short-lived ones this change will be rapid. Nevertheless, as it is impracticable to wait for the disappearance of the whole of the short-period radioactivity of the fission products, it is necessary to arrange to handle the uranium while it still contains highly radioactive substances. In this state, the uranium slug is emitting $\gamma$ rays on such a scale that it cannot safely be approached by human beings; furthermore, the plutonium within the uranium is an intense poison, as are also the radioactive fission products. It is therefore essential that the uranium should be handled by remote control. The general scheme adopted has been described by Smyth.[3] A "canyon" was built consisting of a line of compartments having heavy concrete walls; this was almost completely underground. Each compartment contained chemical equipment for treating the uranium and for extracting the plutonium from it. Uranium entered the line from the pile at one end of the canyon, where it was dissolved; it then went through various chemical processes and from time to time was pumped from one compartment to the next until eventually there came from the last compartment a solution of a plutonium salt which was free from both uranium and from fission products. The processes involved were similar to

* In practice it is unlikely that the uranium slugs remain in the pile for long enough to achieve equilibrium amongst the fission products.

ordinary chemical processes but they were rather complicated and were made more so by the necessity for controlling them from distant points above ground.

Very little information has been given about the actual chemical processes used, but it is worth recalling the nature of the problem and recounting what has been revealed. In the case of the Clinton pile, uranium went to the treatment plant at the rate of about 300 kg. a day. Now this pile, operating so that 1000 kW is liberated as heat, produces about 1 g. of plutonium a day in a mass of uranium that probably lies between ten and one hundred tons. It is neither possible nor necessary to extract daily the whole of the plutonium produced; it is more satisfactory to treat each day a fraction of the uranium in the pile, for in this way there is a welcome increase in the concentration of plutonium in the uranium slugs. If the uranium is handled systematically so that each slug spends the same period in the pile, the plutonium in the uranium which is withdrawn daily from the pile will be equal to the whole daily production of plutonium within the pile. Consequently in the 300 kg. of uranium withdrawn daily from the Oak Ridge pile there was about 1 g. of plutonium with the addition of a similar amount of fission products, much of which was in the form of highly dangerous radioactive substances. Thus the concentration of plutonium in uranium is in this case comparable with the concentration of gold in gold-bearing minerals, but the process of separation is much more difficult here because of the chemical similarity of plutonium and uranium and the presence of the fission products. It must be remembered, too, that when the Clinton pile was first put into operation at Oak Ridge, the chemical studies of plutonium had been made in the laboratory when only very small quantities of material were available. Nevertheless the actual experience with plutonium extraction at Oak Ridge was very favourable. By 1st February, 1944, after the Clinton pile had been in operation at a low reaction level for a period of nearly three months, only 0.190 g. of plutonium had been delivered, but a month later several grams had been separated. From the very first it was found possible to extract 50% of the plutonium within the uranium slugs going into treatment, and by the middle of 1944 this recovery efficiency had been raised to between 80 and 90%. The chemical methods, though very successful, were expensive and complicated, and the work at Oak Ridge gave opportunities for making the improvements which were needed for the much larger scheme at Hanford. In this way the Clinton pile was invaluable; it also assisted progress generally by providing an example of a pile of moderate size in operation, for on this pile operators could be trained and experiments could be carried out with a view to determining the procedure to be adopted for the projected piles at Hanford. Finally it

provided appreciable quantities of plutonium from which physical constants, and particularly nuclear constants, could be determined with accuracy.

The following information has been published concerning the nature of the chemical processes used to separate plutonium from uranium and the fission products. It appears that plutonium has four states of oxidation, corresponding to positive valencies of 3, 4, 5 and 6 and that the separation processes make use of this fact. It is possible to prepare a solution of uranium and plutonium in which the plutonium is in oxidation state 4, to add a suitable carrier and then to precipitate the plutonium and the carrier; with the precipitate is a part only of the fission products. After dissolving the precipitate, the plutonium is brought into oxidation state 6 and the carrier compound is then precipitated in such a way that the plutonium remains in solution. When suitable carriers are used, fission products which precipitate with the carrier in the first stage also precipitate with it in the second. By carrying out a sufficient number of cycles of this type—and apparently it is advantageous in different cycles to use different reagents according to whether it is more important to eliminate uranium or fission products—a very efficient and satisfactory separation process is achieved; this process was available in time to be put into operation when the Hanford piles commenced to deliver plutonium.

(10) *Depletion of $U^{235}$ in a reacting pile.*

It will be realized that a pile operates and is able to produce plutonium by virtue of the presence of the small quantities of $U^{235}$ in the natural uranium which forms the active material of the pile. What happens as $U^{235}$ is consumed? In the long run, of course, if the pile can continue to operate, all the $U^{235}$ will be used up and the pile will continue to run only as long as there is sufficient $Pu^{239}$ to ensure that the reproduction factor can be maintained at the value of unity. In practice, however, the $U^{235}$ is consumed quite slowly as can be seen by remembering that plutonium is produced at about the same rate as $U^{235}$ is consumed. In the case of the Oak Ridge pile, where the plutonium content of the uranium slugs going into solution was 3 parts in 1 million, the consumption of $U^{235}$ had reduced its concentration by only about 0.05%; this reduction in $U^{235}$ content occurs during the period the uranium slug remains in the pile, and as this period probably exceeded a month, the daily reduction in $U^{235}$ content was very small indeed. At Hanford, where the plutonium concentrations were considerably greater than those at Oak Ridge, the daily consumption of $U^{235}$ amounted to a few grams for every ton of uranium in the pile. The consumption of $U^{235}$ tends to lower the reproduction factor of the pile but, on the other hand, the production of $Pu^{239}$, which gives

fission when bombarded by slow neutrons, makes good some of the loss of $U^{235}$, the precise change in reproduction factor depending upon the relative amounts of $U^{235}$ consumed and of $Pu^{239}$ produced. There is also the possibility of a fall of reproduction factor arising from the presence of fission products in the pile. Some of these materials have appreciable neutron capture cross sections and if they are present in great enough quantity the neutron consumption they cause will prevent the operation of the pile. This phenomenon is known as poisoning and no precise information is available about the stage in the operation of a pile at which it becomes significant; in piles which are operated for the plutonium they produce, the uranium slugs are removed from the pile before the depletion of the $U^{235}$, or the accumulation of excessive amounts of neutron absorbing fission products, has occurred to any great extent. These factors, as well as others, must be considered when a decision is being made concerning the time for which a given uranium slug should remain within a reacting pile.

Uranium which has taken part for a long time in a chain reaction in a pile contains a smaller concentration of $U^{235}$ than occurs in natural uranium, and for this reason uranium, from which plutonium has been extracted, is of relatively little use at present for the purposes of releasing atomic energy. A pile which has a reproduction factor greater than unity when natural uranium is used as active material, may be able to operate with uranium having slightly subnormal concentrations of $U^{235}$, but it seems unlikely that simple arrangements can be made to use up the whole $U^{235}$ content of natural uranium, let alone the whole available quantity of $U^{238}$. If this is the case, as it would appear to be in a uranium pile being run for the production of plutonium, one of the most important by-products is uranium which is substandard from the point of view of $U^{235}$. It may well be that this uranium is of use in industry, but for the production of atomic energy its value has been seriously diminished.

(11) *Atomic transmutation in a pile.*

Very little information has been released about the performance of the Hanford piles, and relatively little about the operation of controlled reacting piles in general; for this reason it is impossible to give precise details of many features of the operation of a pile which is being run for the plutonium it yields. The details which have been discussed give some impression of the magnitude of what has been achieved. In 1938 neither uranium fission nor plutonium was known; less than six years later, after a scientific effort of unprecedented magnitude, the first of the giant Hanford piles was brought into action and the transmutation of matter was carried out on such a scale

that a new element, which had been discovered about four years earlier, was being made at a rate which perhaps exceeded 100 g. a day. Not only were the substances and the processes novel; they involved the production of vast amounts of very penetrating and very deadly radiations and the treatment of substances which were intensely poisonous. That this work was carried to a successful conclusion is a tribute to the efforts of the many technicians who were employed directly on this project, and also to the soundness of the fundamental researches which were carried out in nuclear physics during the 1930's. Without these and the experimental techniques which grew around them, the manufacture of plutonium could not have been undertaken.

*REFERENCES*

[1] Smyth Report, 6.35.
[2] Smyth Report, 8.8.
[3] Smyth Report, 8.41.

## CHAPTER XIII

# THE ATOMIC BOMB

(1) *The bomb as a chain reactor.*

The most spectacular achievement in the field of atomic energy has been the successful use of the atomic bomb. Naturally, this device is regarded as a military weapon, and no detailed information has been released concerning it; regarding the most interesting question of the actual means employed in detonating the bomb, the published accounts are either extremely vague or totally unmindful of the widespread desire for information and explanations.

Nevertheless, there is a certain amount of information which can be given, and on matters which are secret some speculation is possible. In the first place, it must be realized that the atomic bomb is only a chain reactor. It differs from a uranium pile in that it is small and is designed to give rise to a chain reaction in which the reproduction factor is as great as can be achieved; furthermore, in the atomic bomb the life time of a generation of neutrons is as small as possible.

(2) *Explosions.*

Let us consider briefly the mechanism of an explosion and the properties of a good explosive. In order to make an explosion, it is necessary to have some mechanism by which the volume of a piece of matter is suddenly increased. An effective explosive is one in which there is a very large increase in volume within a very small interval of time. An explosion may be achieved by the use of an unstable liquid or solid which suddenly liberates a large volume of gas, but most explosives liberate heat in addition to gas. The process of explosion is often very similar to that of combustion; this is illustrated when liquid oxygen comes into intimate contact with powdered charcoal and an explosion results because the charcoal and the oxygen form carbon dioxide and liberate large quantities of heat. Similarly the explosion of gunpowder involves the combustion of carbon and sulphur. The evolution of heat by an explosive is by no means essential, but as it gives rise to an increase of pressure of the released gas, the effectiveness of an explosive is closely related to the heat liberated in the reaction; other factors are also important and will require consideration when an explosive is being chosen for a particular purpose. Nevertheless, an explosive that delivers a large amount of heat energy per unit volume of material is likely to be very effective provided the delivery of heat occurs sufficiently quickly. The heat energy raises to a high

temperature the material of the explosive and temporarily a localized region of high pressure is produced ; the sharp boundary of this spreads as does a sound wave, and regions near the centre of explosion experience a sudden rise in pressure from which much destruction may ensue. Unless the explosion occurs rapidly, it is not complete before the hot products of explosion extend over a rather large volume and this, and the fact that they are diluted with cool air, diminishes the intensity of the explosive wave. We have already seen that nuclear fission is capable of yielding very large amounts of heat energy ; if this process can be carried out quickly, and on a vast enough scale, a terrible explosion must occur. In principle, then, a nuclear fission chain reaction which is rapid and which grows to a sufficient magnitude to result in the fission of some pounds of material will provide an atomic bomb.

(3) *Requirements of an atomic bomb.*

We have already mentioned that the energy released in the fission of 1 lb. of uranium exceeds that liberated when two million pounds of coal are burned ; the same amount of energy may be produced from the explosion of nearly 10,000 tons of T.N.T. The real problem was that of arranging a bomb in which a reasonable portion of the fissionable material present was caused to yield its energy before the bomb and the products of explosion began to disperse themselves ; it was further desirable that the bomb should not be too large and that it should not contain an undue quantity of very rare material ; finally it was essential that the bomb should not detonate by accident, and that its instant of detonation should be subject to reliable control. The task of devising an atomic bomb involved the determination of an arrangement which would give rise to a chain reaction of the desired type and the perfecting of a suitable mechanism for commencing the chain reaction at the desired moment.

Let us consider the necessary means for achieving an atomic bomb. We shall imagine that supplies of suitable fissionable material are available, and we shall suppose that we have a number of small bricks of this material ; from them we commence to build a cube. Because of the existence of stray neutrons, on occasion there will occur the fission of an atom within the structure we are building, and this fission will give rise to fast neutrons. Now all materials have small capture cross sections for fast neutrons so that before neutron capture occurs the neutrons released will travel some considerable distance, in which they may lose energy as a result of interactions with the matter through which they pass. It may happen of course that a neutron escapes from the structure before it is captured, and in that case it will have no further influence unless it is reflected back again. Even if a neutron is

captured before it leaves the structure, it will not necessarily give rise to fission, not even if the material used is free from neutron absorbers like $U^{238}$, for even though a nucleus is excited with sufficient energy to give the deformation which is followed by fission, cases will occur in which the excess energy results in neutron or $\gamma$ ray emission rather than in fission. In the most favourable circumstances, then, an atomic bomb will be made from a substance in which the neutron binding energy exceeds $E_f$—the energy which is sufficient to give the deformation from which fission arises—by so much that the capture of a neutron is almost certainly followed by fission. This requires that the atomic bomb is made from a material which gives fission on the capture of a slow neutron, not because slow neutrons are of significance in the explosion of an atomic bomb, but because this requirement gives the best possible chance that fission will result from the capture of a fast neutron; in fact it ensures that fission is highly probable upon the capture of a neutron of any energy. In terms of present knowledge, the best materials for an atomic bomb are $U^{235}$ and $Pu^{239}$; it is probable that $U^{233}$ is also suitable.*

It will be appreciated from earlier discussions that the size of the structure being built will determine whether or not one fission results, on the average, in a further fission, and that size determines whether the chain of fissions grows or dies. If the structure is just smaller than the size at which the reproduction factor is unity, the structure is said to be below the critical size, and in this condition, if k is the reproduction factor, a single fission will be followed on the average by $\frac{k}{(1-k)}$ further fissions. As explained earlier,† from observations of the number of neutrons released in the structure when a beam of neutrons falls on it, k may be determined; if desired further bricks may be added in order to bring the reproduction factor up to unity. If the reproduction factor is made just greater than unity by increasing sufficiently the size of the structure, a chain reaction will be initiated by a single fission and the spontaneous reaction of the structure will commence; fissions will occur at a steadily increasing rate, but there will be no large explosion, because if k is not much greater than unity the growth of the fission rate will depend upon the emission of delayed neutrons and it will occur relatively slowly. At this stage, however, it is desirable that steps be taken to stop the growth of the chain reaction, for otherwise the fission rate will increase so far that at the least there will be emitted excessive and unsafe amounts of radiation.

Let us consider some of the details of a chain reaction with a view to making an estimate of the critical size of an atomic bomb. In the interests of

* $U^{233}$ may be derived from thorium. (See footnote, Chap. XI, p. 112.)

† Compare Chap. XI, p. 120

simplicity, (and as we cannot hope to achieve accuracy we can afford large sacrifices in aid of simplicity) we shall assume that every fission results in the release of two neutrons. We shall assume, further, that our atomic bomb is a sphere, and that the neutrons released upon fission have a certain path length in the sphere before they cause fission. We are interested first of all in determining the critical size, when the reproduction factor just attains the value of unity. If the radius of the sphere is just equal to the free path of the neutron, and if the neutron path is a straight line, more than half of the neutrons will escape without making a further fission, so that if two neutrons arise per fission a chain reaction will not be possible unless an adequate reflector encloses the fissionable material. If the size of the sphere is somewhat increased, neutrons formed near the centre will rarely escape and the advantage arising here may compensate for the excessive losses occurring in other regions of the sphere. Without the use of a reflector, the critical radius is somewhat larger than the distance the neutron moves in a straight line; with it, the critical radius will be smaller, perhaps considerably smaller, if the reflector returns an appreciable fraction of the neutrons which would otherwise leave the reacting system. It will be understood that the critical size depends on the shape of the fissionable material; the shape considered here is spherical, but the conclusions are sufficiently vague to be applicable to shapes which do not depart very far from the spherical.

To make further progress in this consideration of the critical size, we need to know what figure to use for the path length. We take for this quantity the mean path length between the emission of a neutron and the fission produced by it. This latter quantity is secret and we can do no more than estimate it from other data. It is likely that the capture cross sections for fast neutrons of given energy in $U^{238}$, $U^{235}$ and $Pu^{239}$ are very much the same, so that if we knew the correct value for $U^{238}$ we would have a useful figure to employ for whatever fissionable material is used in an atomic bomb. As the capture cross section of $U^{238}$ for fast neutrons does not appear to have been published, we must base our estimate on the fission cross section of this nucleus[1]; for 2.5 MeV neutrons it is $5 \times 10^{-25}$ cm$^2$. Now when $U^{238}$ captures a fast neutron, it is more likely to release surplus energy by neutron emission than by fission, and as every capture does not result in fission, the capture cross section is considerably greater than the value quoted for the fission cross section. For the capture cross section of $U^{238}$ we guess the value of $1.5 \times 10^{-24}$ cm.$^2$ In the case of $U^{235}$ the capture of a neutron most probably results in fission, so that for this nucleus capture and fission cross sections are almost identical. This leads to the conclusion that the fission cross section for $U^{235}$ is about $1.5 \times 10^{-24}$ cm.$^2$ for 2.5 MeV neutrons; for slower ones it is likely to be still greater. The same arguments apply to plutonium, although in view

of the large amount by which the neutron binding energy exceeds that required to initiate fission, in this case the capture of a fast neutron is almost certain to result in fission, and consequently the fission cross section of plutonium may be somewhat higher than that of $U^{235}$.

If the densities of these fissionable materials are about 20 g. per cm.$^3$ each cm.$^3$ will contain about $5 \times 10^{22}$ atoms; consequently the path of a neutron will average about 13 cm. Now a sphere of uranium of radius 13 cm. has a volume of about 9 litres and a mass of 180 kg., and in view of our estimates of critical size, the bomb would exceed this mass. Although the Smyth report is very vague about the mass of material required to make an atomic bomb, it gives the limits of between 1 and 100 kg. It will be appreciated that the estimates given above are based on the crudest assumptions, and that the mass of the bomb is very sensitive to the value chosen for the critical radius. Furthermore, no account has been taken of the effect of surrounding the bomb by a reflector, of the favourable effects of non-capture collisions between neutrons and the material of the bomb,* or of the possibility that the average number of neutrons emitted per fission is sufficiently in excess of two to cause an appreciable decrease in the critical size and mass. Even if the estimate of critical mass had been in closer accord with expectations, great uncertainties would still have existed; the only value of an estimate is to help to present the factors on which the critical size depends.

Let us now discuss the factors which determine the life time of a generation of neutrons. A neutron emitted with an energy of 2 MeV moves with an initial velocity of $2 \times 10^7$ metres per second, so that such a neutron takes about $6 \times 10^{-9}$ sec. to move the distance of 13 cm. which we estimate as the average path length between the place of emission of a neutron and the fission caused by it. For somewhat slower neutrons, the fission cross section will be somewhat larger, the path length will be shorter and fission will occur in about the same average lapse of time. This gives an approximation to the life time of a generation of neutrons, for the time between neutron capture and the occurrence of fission is quite negligible compared with the average time which elapses between the emission of a neutron and its subsequent capture. In addition to the life time of a generation of neutrons, we require to know for how long the explosion can continue without loss of catastrophic effect. Perhaps no precise limit can be determined; doubtless the matter has been carefully considered by those who were concerned with the design of the bomb, but no official information has been released concerning it. At a guess it seems reasonable to assume that the explosion should be completed

* Such collisions deflect the neutron and increase the distance it travels before it escapes from the bomb.

within a period of 1 $\mu$sec. ($10^{-6}$ sec.); to achieve so rapid an explosion will not be reasonably possible if the neutron generation life time appreciably exceeds our estimate of $6 \times 10^{-9}$ sec.

In order to make clear a number of points, let us assume that we have an atomic bomb for which the reproduction factor is 1.2 and the neutron generation life time is $6 \times 10^{-9}$ sec. We suppose that a chain reaction commences with a single fission. One microsecond* later, in the 167th generation of neutrons, there will be about $16 \times 10^{12}$ fissions, and altogether in this period of 1 $\mu$sec. there will have been a total of $8 \times 10^{13}$ fissions. Nevertheless, as this number of fissions corresponds to about $3 \times 10^{-8}$ g. of uranium, it releases insufficient energy to cause a marked rise in the temperature of the bomb, let alone an explosion. At first sight this is a disappointing result; it appears that the circumstances assumed—and they looked reasonably favourable—are such that the chain reaction grows too slowly to produce a serious explosion. In fact, however, the process is just starting up, and the period that has elapsed, although apparently wasted, has involved no detrimental effect to the subsequent performance of the bomb. In the next interval of 1 $\mu$sec., there are $12 \times 10^{26}$ fissions, provided, of course, that the necessary uranium is still available; the quantity consumed would amount in this case to 500 kg.

Let us see what appear to be the minimum requirements for a successful atomic bomb. An adequate explosion is likely to be produced by the fission of a few pounds of uranium, and to achieve this $10^{24}$ or more fissions must take place within a period which should be less than 1 $\mu$sec.; as it is hardly likely that a bomb can be made in which one fission gives rise to $10^{24}$ fissions within a period of 1 $\mu$sec., we are faced with the problem of deciding on the maximum allowable number of fissions before the explosion is said to begin. If we assume that the bomb contains 20 kg. of fissionable material and that the explosion begins when the uranium temperature has risen to 150°C., we find that this state of affairs has been reached after $10^{16}$ fissions. The explosion then occurs in the period in which the number of neutrons in a generation increases by a factor of $10^8$ or more. If the reproduction factor is 1.2 this will require at least 100 neutron generations, if it is 1.4 about 55 generations will be required, and if it is 1.6 an adequate explosion will occur after 40 neutron generations. In practice, then, the period of the explosion depends upon the attainable value of the reproduction factor and on the neutron generation life time. To assume that the reproduction factor exceeds 1.2 would seem optimistic; it likewise appears unreasonable to suppose that the life time of a neutron generation is very much less than the value of $6 \times 10^{-9}$ sec. already assumed. Unless these figures are much in

* 1 microsecond may be written as 1 $\mu$sec. It is $10^{-6}$ seconds.

error, the explosion, as we have defined it, requires a period of at least 0.6 $\mu$sec. It is to be observed, however, that we assume a chain reaction that grows steadily throughout the explosion, and as a result in the last period of 0.1 $\mu$sec. there is liberated about 95% of the total energy of the explosion. The results of these calculations do not agree with a statement in *One World or None*[2] to the effect that the time of explosion of the atomic bomb is about $10^{-7}$ sec. ; as it is uncertain whether the estimate is made on the basis used here, the value is mentioned only in view of the authority behind it.

The figures derived here serve to show how necessary it is to achieve a high reproduction factor and the minimum possible neutron generation life time. In the case of a 20 kg. bomb the fission of $10^{24}$ uranium atoms involves the consumption of only about 2% of the fissionable material of the bomb ; nevertheless, if uranium had its usual specific heat at all temperatures the heat equivalent of the energy released in $10^{24}$ fissions is enough to raise the temperature of the uranium in the bomb to $10^{10}$ °C.

It will be realized that although a high reproduction factor helps to give a very rapid explosion, high reproduction factors can be achieved only by using large bombs. A larger bomb may be more destructive, but it will certainly require greater amounts of fissionable material and on balance the more effective explosion may not compensate for the greater consumption of this material. Whatever the size of the bomb, it seems desirable to arrange it so as to make as large as possible the reproduction factor and the period during which the chain reaction can usefully take place.

From the point of view of a short generation life time, a neutron reflector around the bomb is a doubtful advantage. It will certainly return neutrons, but if it is of real service it must return these neutrons quickly ; time that a neutron spends in the reflector represents lost opportunities for causing fissions, and unless the neutron returns quickly to the fissionable material, its contribution to the fission process will be so long delayed that it will not give adequate assistance to the rapid build up of the chain reaction. On the other hand, the reflector, which should be made of heavy material, has a considerable mass and its inertia tends to prevent the spread of the materials of the bomb in the earlier stages of the explosion.

During the development of the chain reaction there is liberated a vast quantity of energy some of which is in the form of penetrating $\gamma$ rays ; much of this energy escapes immediately from the system. The kinetic energy of the fission products and of the fission neutrons is communicated as heat energy to the material of the bomb, and once the chain reaction is proceeding at high intensity the bomb rises rapidly in temperature. This temperature rise, which gives to uranium atoms velocities which are not negligible com-

pared with the velocities of some fission neutrons, may well produce changes in the probability of neutron capture and hence in the reproduction factor of the bomb; but the main consequence of the liberation of heat is to produce high pressures and temperatures and the emission of light, heat and ultra-violet rays appropriate to the temperature of the material of the bomb: in these radiations quite appreciable amounts of energy leave its immediate vicinity. In the bomb itself the high pressures, which are said to reach a value of $10^{13}$ atmospheres, tend to cause its material to fly apart, and during the early parts of the explosion the forces developed are engaged in accelerating the external portions of the bomb. Any resulting enlargement of the bomb will cause a diminution of uranium density and an increase of the neutron path length by more than the increase of linear dimensions of the bomb: on this account the reproduction factor will decrease and at the same time there will be an increase in the neutron generation life time. Furthermore, uranium is being consumed and is replaced by fission products. Each of these changes causes a reduction in the rate of build up of the chain reaction, and eventually the expansion of the bomb and the conversion of the materials within it will proceed sufficiently to reduce the reproduction factor to values less than unity, at which the chain reaction dies down. The explosion will be most effective if the expansion can be delayed until the bulk of the uranium has been subjected to fission, and the neutron reflector around the bomb serves to provide a heavy mass which must be removed by the forces of explosion and the presence of which materially delays the expansion. Nevertheless, within a few microseconds at the most the explosion is over and the atomic bomb has become an incandescent mass which consists of unused fissionable material, the fission products and all apparatus which was in close proximity to it.

The high temperature of this material results in a great upward air current and the fission products and the fissionable material, all of which are poisonous, are carried to a great height in the atmosphere and are eventually deposited very thinly over a vast area of the earth. There was reason to suppose that in the immediate neighbourhood of an exploding atomic bomb the earth would be strewn with radioactive fission products which would make human existence impossible, but if the bomb is exploded at some considerable height above the earth there is no undue concentration of radioactive substances at points near the explosion. This does not mean, of course, that there is any chance of safety in the vicinity of an exploding atomic bomb, for not only is there a most intense explosion wave, but the bomb emits large quantities of $\gamma$ rays. These $\gamma$ rays are rather less in amount than might be expected from the calculations relating to an operating pile, because during the explosion of the atomic bomb there is only a small amount of radiation

from the fission products, which are so quickly carried away by the upward stream of hot air. Most of the $\gamma$ rays emitted come from the excitation energy of the primary fission nuclei. As has already been stated, 1 g. of radium gives $\gamma$ rays from $4 \times 10^{10}$ disintegrations per second, and at 1 metre distance these give an ionization of $4 \times 10^5$ ion pairs per cm.$^3$ per sec., i.e., $2 \times 10^{-4}$ r units per sec. Now we believe that a successful atomic bomb should involve $10^{24}$ fissions at least, so that the $\gamma$ rays emitted may produce $10^{19}$ ions pairs per cm.$^3$ or $5 \times 10^9$ r units at 1 metre. It may be that on many occasions the primary fission nuclei do not emit $\gamma$ rays, but even if this view is accepted the total $\gamma$ radiation at a distance of 1 metre can hardly be less than $10^9$ r units. At 1 km. from the bomb there has been considerable $\gamma$ ray absorption by the air, and the dose of radiation might be about 5 r units; at half this distance the total radiation is much larger and might reach 300 r units, an amount which will often be fatal. These figures are only approximate, but they serve to show that even at considerable distances from an atomic bomb death may result from $\gamma$ radiations as well as from the effects of the explosion wave.

It is probable that the most difficult problem connected with the atomic bomb was that of arranging a satisfactory method of detonation. A piece of $U^{235}$ or of plutonium is quite safe as long as it is smaller than the critical size, but when this size is exceeded the onset of a chain reaction will not be long delayed; there are stray neutrons passing through the atmosphere, a neutron may be formed as a result of a collision between an $\alpha$ particle emitted by $U^{235}$ or plutonium and an atom of impurity, or a nuclear fission may take place spontaneously, a process which though infrequent is occurring once every few seconds in a kilogram of $U^{235}$ or $Pu^{239}$. It is imperative that the bomb should be built from two or more masses of fissionable material, each less than the critical size and so separated from one another that a chain reaction is impossible. When detonation is required, these masses are brought into close contact; precautions must be taken to avoid the commencement of the chain reaction before contact is established, and to initiate it immediately the component parts of the bomb are united. At this stage the material of the bomb must be exposed to the neutrons from a neutron source, for only in this way can the commencement of the chain reaction be made to occur close to the moment of contact. The example of the rate of neutron growth, already considered, shows that there is no utility in commencing the chain reaction by trying to introduce many neutrons simultaneously into the fissionable material, for the number of neutrons which exist, 1 $\mu$sec. after a single fission initiates a quickly growing chain reaction, is much greater than the number of neutrons arising even in one second from any neutron source of convenient size. For this reason the chain reaction begins at the moment of

the first fission and neutrons entering the system a fraction of a microsecond later produce only negligible effects.

Fig. 32 gives a representation of the paths of neutrons in the initial stages of a chain reaction in a bomb. Within the inner circle is fissionable material and surrounding it is a neutron reflector. The chain commenced with fission (1), brought about by a neutron which started at 0 in the centre of the bomb. This fission gave two neutrons, of which one was lost. The consequences of other fissions are readily seen. This diagram shows a case in which the reflector makes an important contribution to the build up of the chain reaction. Non-capture collisions are frequent; without their effects the fraction of neutrons escaping would be too large to permit the growth of the chain reaction.

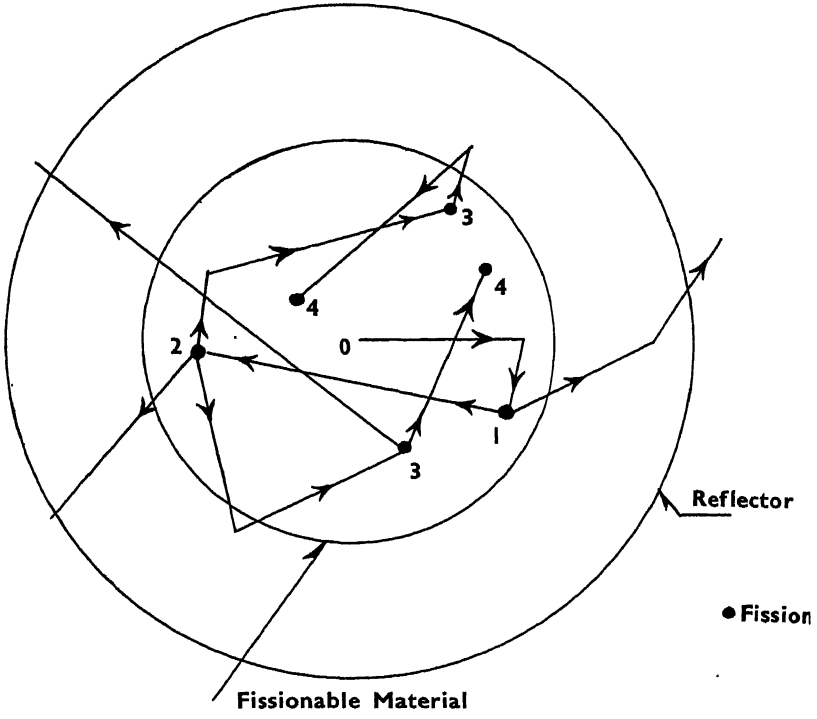


**Fig. 32.** The beginning of a fast-growing chain reaction.


**Fig. 33.** The New Mexico atomic bomb explosion. 0.016 sec. after detonation.
(Reproduced by courtesy of the Directorate of Atomic Energy, Ministry of Supply.)

With reference to the means adopted for the detonation of the bomb, it is clear that one part of the fissionable material may be a projectile which is shot from a kind of gun into another portion of the bomb; the speed of projection must be high enough to ensure that there is no danger of the onset of a chain reaction before the two parts are close enough to allow it to grow quickly to a high intensity. Although this means of detonation is obvious, and is discussed briefly in the Smyth report,[3] it is by no means simple in detail and from the remarks that Smyth makes it is clear that alternative methods of detonation were considered. As there is hardly any information available on this interesting matter, it is not profitable to discuss it further.

It is worthy of note, however, that the task of devising an atomic bomb involved a difficulty which is most unusual in engineering experience: there was no possibility of trying out the bomb or the means of detonation by the use of a small model. Difficulties of a similar nature arose throughout the work on the atomic bomb; the first experiments were handicapped by lack of fissionable material, but even when this was available in quantity it was still necessary to base the design of the atomic bomb on the results of studies


**Fig. 34.** The New Mexico atomic bomb explosion. 0.053 sec. after detonation.
(Reproduced by courtesy of the Directorate of Atomic Energy, Ministry of Supply.)

which could not include a chain reaction such as was to be used in the actual bomb.

In ordinary engineering, it would be regarded as difficult to design a bomb to make efficient use of a material which was said to be explosive but which, for some reason, could not be detonated before it was assembled in a bomb; the task would be made more difficult if the problems of detonation imposed similar restrictions to those arising from the use of fissionable material. It was only incidental that the bomb depended on the use of materials which were many times rarer and more costly than gold, but it made it essential that the bomb should succeed on the first attempt. Above all, when it is remembered that the action of the bomb depended on the use of a recently discovered nuclear process which had never before been used to give an explosion, it will be realized that the successful construction of the atomic bomb was a feat of the greatest difficulty and one which perhaps has never been surpassed in the history of science or engineering. The success of this work lends powerful support to the statement that "the end of 1944 found an extra-


**Fig 35.** Aerial photograph of the site of the New Mexico atomic bomb e
28 hours after detonation.

(Reproduced by courtesy of the Directorate of Atomic Energy, Ministry of Supply

ordinary galaxy of scientific stars gathered on this New Mexico mesa in reference to the personnel at Los Alamos in New Mexico where th bomb was designed, constructed and assembled.

On 16th July, 1945, at 5.30 a.m., the first atomic bomb, mounted steel tower, was detonated. There was a blinding flash which illumi surrounding country more brightly than the brightest day, the ma the bomb were raised to a temperature exceeding that of the interi sun, and very soon afterwards a huge many-coloured cloud, conta products of explosion, had risen to a height of 40,000 ft. Where

tower had stood was a large shallow crater on the surface of which was a jade-like substance which had previously been grains of desert sand. Figs. 33 and 34 are photographs taken within a tenth of a second of the instant of detonation of the bomb. Fig. 35 gives an aerial view of the bomb site after the explosion; the region within which the sand was fused surrounds the site of the bomb and appears as a rather irregular dark patch.

Such were some of the results of the explosion of an atomic bomb in the waste lands of New Mexico. Words fail to describe the consequences of atomic bomb explosions over densely populated regions of Japan*; even to-day I find it difficult to understand the inhumanity of the man or men who decided to reveal the atomic bomb to the world by using it in such a way.

* A description of the effects of the Hiroshima bomb is given in *One World or None*[5]. See also *The Effects of the Atomic Bombs at Hiroshima and Nagasaki*[6].

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[2] *One World or None*, McGraw-Hill, 1946 : p. 14.
[3] Smyth Report, 12.19 and 12.20.
[4] Smyth Report, 12.5.
[5] *One World or None*, McGraw-Hill, 1946 : p. 1.
[6] H.M. Stationery Office, S.O Code No. 34-312.* (1946).

## CHAPTER XIV

# THE SEPARATION OF THE URANIUM ISOTOPES

(1) *General considerations.*

In our discussion of atomic energy, the use and properties of $U^{235}$ have frequently been mentioned, but nothing has yet been said about the process of separating it from natural uranium, in which it occurs to the extent of 0.7%. When the existence of isotopes was established, it was realized that they could not be separated by any chemical process, but from time to time experiments were made with a view to separating them by making use of some physical difference between them. Isotopes differ in mass and of course in properties which are connected with their mass ; nevertheless, it is difficult to find such a property which gives good prospects of separating isotopes in any quantity, and prior to 1940 in the case of heavy hydrogen only had it proved possible to separate isotopes on any considerable scale. Because the mass of heavy hydrogen was double that of the common isotope, separation was relatively easy and could be effected by the electrolysis of water ; it was realized that success in this instance afforded no promise of success in cases like that of uranium in which the isotopic masses differed only by a few percent., and that for such cases electrolysis was unlikely to be useful.

(2) *Porous barrier method of separation.*

In a mixture of gases in temperature equilibrium, every kind of molecule has the same average kinetic energy, although individual energies are spread over some considerable range ; this means, on the average, that light molecules move faster than heavier ones, and it also means that in a mixture of equal numbers of light and heavy molecules the former make more collisions with the walls of the containing vessel than do the latter. If we arrange that the containing vessel is made of a porous material with very small holes in it, fast light molecules will more frequently enter these holes than heavy slow ones. If every atom or molecule which enters a hole is able to leave the vessel through the porous wall, we shall find that the gas issuing is richer in light molecules than was the original gas. The process by which gas molecules pass through a porous membrane is known as diffusion. It is not necessary to restrict ourselves to mixtures of equal numbers of light and heavy molecules, for diffusion produces a similar change in concentration whatever the initial proportions. It has long been known that this process is capable

of separating a light gas from a heavy one; thus in this way hydrogen $^{235}F_6$ been separated from oxygen or carbon dioxide.

Two points connected with the process are worth further consideration. The gas that goes through the membrane should be prevented from diffusing back again, for if this happens, the initial increase in concentration of the light molecules on one side of the membrane will eventually disappear. To retain the advantage achieved, the gas must be pumped away immediately it diffuses from the membrane. The other point is equally obvious. If there is an increased concentration of light molecules on one side of the membrane, there must be a decreased concentration on the other side, so that as the diffusion proceeds the gas in the first container becomes impoverished in light molecules and there is a steadily decreasing advantage in continuing the process. If the most rapid increase in concentration is to be achieved, it is necessary to allow the diffusion of only a small portion of the available gas; this, however, is not practicable, because the relatively rapid increase in concentration is associated with a very small yield. In practice a considerable fraction of the gas must pass through the membrane even though this involves more diffusion stages to achieve a given separation of light and heavy molecules.

The feasibility of an isotope separation process depends on many factors, but of these one is of paramount interest and importance: it is a ratio which we call the enrichment factor. The value of this quantity is obtained by comparing the concentration ratio of wanted to unwanted components at two stages of the separation process; the enrichment factor is defined as the higher concentration ratio divided by the lower.* An example helps to clarify the meaning of this term. In natural uranium, the ratio $U^{235}$ : $U^{238}$ is about 1 : 139. If it is desired to obtain 90% $U^{235}$, the final ratio $U^{235}$ : $U^{238}$ is 9 : 1 and the necessary overall enrichment factor is $139 \times 9$, i.e., 1251. Or, again, an enrichment factor of 139 will give 50% $U^{235}$ from natural uranium. An advantage of using this enrichment factor arises when different stages in a separation plant involve different enrichment factors, for in such a case the overall enrichment factor, from which the nature of the output product is determined, is simply the product of the enrichment factors for the various stages.

Let us determine what enrichment factor can be achieved by the diffusion method when the isotopes of uranium have to be separated. Unfortunately it is necessary to make use of uranium hexafluoride, $UF_6$, a substance which

* This quantity is what Smyth[1] calls the separation factor; his enrichment factor is obtained by subtracting unity from the quantity used here. As there is no separation it appeared well to avoid the use of the term "separation factor."

is a solid at normal temperature and pressure, but which vaporizes read temperatures not inconveniently high. As fluorine consists of a single isc $UF_6$ contains two different types of molecules, $U^{235}F_6$ and $U^{238}F_6$.* U difficult to handle because of its corrosive properties, and apart fro advantages arising because of its low vaporization temperature an existence of only a single isotope of fluorine, it appears to have few attr properties; it would certainly not have been used in the diffusion proces a more satisfactory alternative compound been available. As the additi six fluorine atoms to an atom of uranium increases the mass by 114 the masses of the two types of $UF_6$ molecules are 352 and 349, and the sion process has to be used to distinguish these two molecules, which in mass by less than 1% and in average velocity by only 0.43%. Wh consider the theoretical enrichment factor in a diffusion process, we fin it is equal to the ratio of the mean velocities of the two gases, so that plant using uranium hexafluoride to separate the uranium isotopes it is 1. If we wish to attain an overall enrichment factor of about 1200 it w necessary to put the gas through about 1700 stages.

(3) *Theory of diffusion separation.*

A simple theory of diffusion may be derived by assuming that the numl molecules diffusing in unit time is proportional to the number of mol striking the porous membrane. One then finds that each isotope diffu a rate which is proportional to the velocity of the molecules and to

> gas passing through the membrane is enriched in the
> a corresponding impoverishment of the gas which ha
> entually the diffusing gas is no richer—and might ev
> nat with which the process commenced. In practice

50% of the gas in each stage was diffused through the porous memb the theoretical enrichment factor for the first fraction of gas is 1.0043, bu factor falls steadily as the gas diffuses, and by the time half the gas has p through the membrane it is only 1.0013. The enrichment factor for a gas which passes through the membrane is theoretically 1.0030. In experiments, diffusion backwards through the membrane and imp mixing of the gas to be diffused were found to make the enrichment considerably less than the theoretical value; the enrichment achieve only 1.0014. Apparently this figure was improved upon, for it is cer not sufficient to give a yield of 99% pure $U^{235}F_6$ in 4000 stages, a perfor which Smyth considers to be possible if each stage has a "reason enrichment factor. This official statement need not be interpreted as me

* Throughout this chapter we take no account of the presence of $U^{234}$ a

that there were 4000 stages in the diffusion plant or that it produced $U^{235}F_6$ of 99% purity.

Let us consider the general arrangement of a uranium diffusion plant. It is evident that a cyclic process must be used in which the output from one stage is passed on to other stages; such a process is often referred to as a cascade process. It will be appreciated that it is not normally desirable to discard the impoverished output material from any stage, for this material is in practice very little poorer than the enriched output of the same stage. It was considered advantageous to have the impoverished output from one stage as rich as the input to the stage below, and it was then arranged that this impoverished output was fed into the stage below that from which it was produced. For a plant which gives a very small enrichment factor per stage, this is achieved by passing nearly half the material to the next higher stage and returning the remainder to the next lower stage. Unless the raw material is so cheap that the impoverished gas from the first stage can be thrown away, it is necessary to have a number of stages set aside for handling impoverished material only. These stages form what is known as the " stripping " cascade; in practice some hundreds of stages may be required, but the actual number cannot be determined without knowing the point at which it is more easily practicable to obtain further supplies of uranium hexafluoride than to add and operate further stages in the stripping cascade.

The difficulty of the diffusion separation method can only be appreciated by considering the sizes of the various stages of the plant; we shall assume that the size of a stage is equal to the volume of gas handled by that stage in order to obtain unit volume of output from the plant. To simplify the discussion we shall first suppose that the concentrating cascade delivers pure $U^{235}F_6$, and that the stripping cascade delivers gas in which there is no trace of $U^{235}F_6$, even though no plant could be made to achieve such a separation.

We imagine a unit volume of gas introduced at the first stage; about half this gas constitutes the enriched output of the first stage and goes through the rest of the concentrating stages; the net result of these stages is to remove sufficient $U^{235}F_6$ to reduce the enriched output from the first stage to the concentration at which it entered the stage. In a similar way the stripping stage removes a quantity of $U^{238}F_6$ sufficient to bring the impoverished material from the first stage to the concentration at which it entered that stage. Numerical values show how small are the amounts of $U^{238}F_6$ and $U^{235}F_6$ removed, and what a large fraction of the gas is returned to the first stage for recycling. Suppose that we admit 280 cm.$^3$ of gas containing 2 cm.$^3$ of $U^{235}F_6$. If the enrichment factor per stage is 1.003, we find that after this gas has gone through the first stage we have nearly 140 cm.$^3$ of enriched gas

containing 1.003 cm.³ of $U^{235}F_6$ and 140 cm.³ of impoverished gas containing 0.997 cm.³ of $U^{235}F_6$. From the enriched gas 0.003 cm.³ of $U^{235}F_6$ is removed by the rest of the concentrating cascade; from the impoverished gas the stripping cascade removes $139 \times 0.003$ cm.³ of $U^{238}F_6$. Consequently, the passage of 280 cm.³ of gas through the first stage yields 0.003 cm.³ of $U^{235}F_6$; to yield 1 cm.³ of $U^{235}F_6$ and 139 cm.³ of $U^{238}F_6$ there must pass through the first stage about 93 000 cm.³ of natural uranium hexafluoride, and of this only 140 cm.³ is new material. Later stages of a diffusion plant are smaller than the first stage, but the decrease in size depends on the value of the enrichment factor per stage, and for the case considered above it is about 0.3% per stage. The smallest stages of the stripping cascade are those handling the most impoverished material, but in the case of a stripping cascade with an output of pure $U^{238}F_6$, or even of very highly impoverished material, the decrease in size is much slower than for the concentrating cascade.

In practice, of course, the material is withdrawn from the diffusion plant either enriched or impoverished and not as we have assumed as perfectly separated products. It turns out that the presence of the stripping cascade has no effect upon the relative sizes of the stages in the concentrating cascade, for clearly the stripping cascade is only a device for bringing impoverished material to the same concentration as in natural uranium so that it may be used again, instead of new $UF_6$, as working material for the concentrating

On the other hand, the concentration of $U^{235}F_6$ in the output discarded from the stripping cascade has a great influence on the of new input material required for a unit output of $U^{235}F_6$ of given

he sizes and number of the concentrating stages are determined mainly by n, the enrichment factor per stage. For a given volume of output, the capacities of the individual stages are somewhat affected by the concentration at which the enriched material is withdrawn from the diffusion plant. If the overall enrichment is 100 or more, the output of 1 litre of $U^{235}F_6$ necessitates the passage of $\frac{280}{n-1}$ litres of natural $UF_6$ through the first stage, so that for an enrichment per stage of 1.003, the passage of about 93 000 litres through the first stage still yields 1 litre of $U^{235}F_6$. It is vital that n should be as close as possible to its theoretical value; any increase in n results in a reduction in the number of stages and a decrease in their size.

If a diffusion plant is arranged to give an overall enrichment factor of 139, the output will consist of material containing 50% $U^{235}F_6$. In this case, supposing again that the enrichment per stage is 1.003, the passage of 93,000 litres through the first stage will yield 2 litres of material at this concentration.

If then the size of each stage is expressed in terms of the volume of output material,* the absolute volumes at the early stages will depend on the concentration at which the enriched material is withdrawn from the concentrating cascade. In the case of overall enrichments in excess of 100, the sizes of the early stages form a geometric series with a common ratio close to $\frac{1}{n}$.

Many features of an ideal diffusion plant can be appreciated by considering the way in which the volume of circulating gas varies from stage to stage. In order to make the matter clear, some figures have been obtained for the case of a plant with an enrichment factor of 1.003 per stage. It is assumed that there are seventeen hundred stages in the concentrating cascade, sufficient to give an overall enrichment of 163 and to deliver $U^{235}F_6$ at 54% purity. The stripping cascade is assumed to contain about 232 stages, so that the impoverished $UF_6$ contains just half the $U^{235}$ concentration of natural uranium. In Fig. 36 are shown the first few stages of the stripping and concentrating cascades. Each stage is represented by a circle; the horizontal line to the right of each circle carries enriched material to the next higher stage and that going to the left carries impoverished material to the stage below. The vertical lines carry the input material either after being enriched by the stage below or impoverished by the stage above. Inside the circle representing

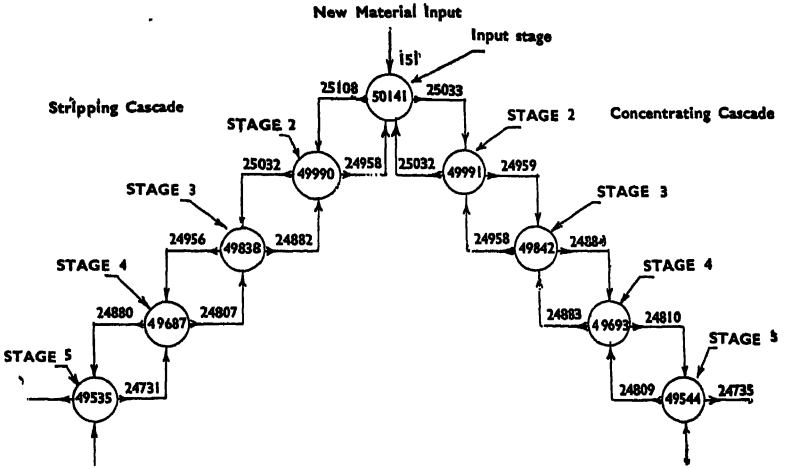


**Fig. 36.** The first stages of an ideal uranium diffusion plant.

* Smyth[8] stated yield in terms of the $U^{235}F_6$ content of the output.

each stage is a number which gives, as do similar numbers on each supply or output line, the number of litres of gas passing through it for 1 litre of output. The values given are those which satisfy the condition that the impoverished output from one stage has the same $U^{235}F_6$ concentration as the supply material to the stage below. The diagram shows how large is the gas circulation in the early stages. It will be noticed that in the concentrating cascade the net flow of material from any stage to the one above it is just 1 litre, as it must be, because of course gas is not accumulating in any part of the cascade.

The new material admitted to the system is 151 litres of which $\frac{1}{140}$ is $U^{235}F_6$. The output of enriched material is 1 litre containing 0.54 litres of $U^{235}F_6$; the balance of the $U^{235}F_6$, amounting very nearly to 0.54 litres, is discarded from the stripping cascade.

Fig. 37 depicts the last few stages in the concentrating cascade, the beginning of which was illustrated in Fig. 36; the only notable features of these stages are their small size and the rapidity with which it decreases.

In Fig. 38 is a graph showing the stage size throughout the assumed ideal diffusion plant, again in terms of one volume of output material containing 54% $U^{235}F_6$. This shows that nearly half the stages handle more than 4000 times the volume of the output material and, as may be estimated from the graph, the total circulation of material through all stages of this concentrating cascade exceeds ten million times the volume of output. In Fig. 38 there

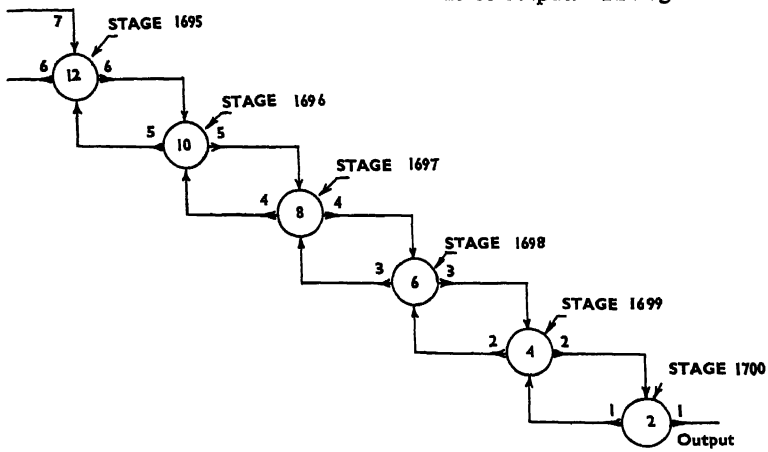


**Fig. 37.** Output stages of an ideal uranium diffusion plant.

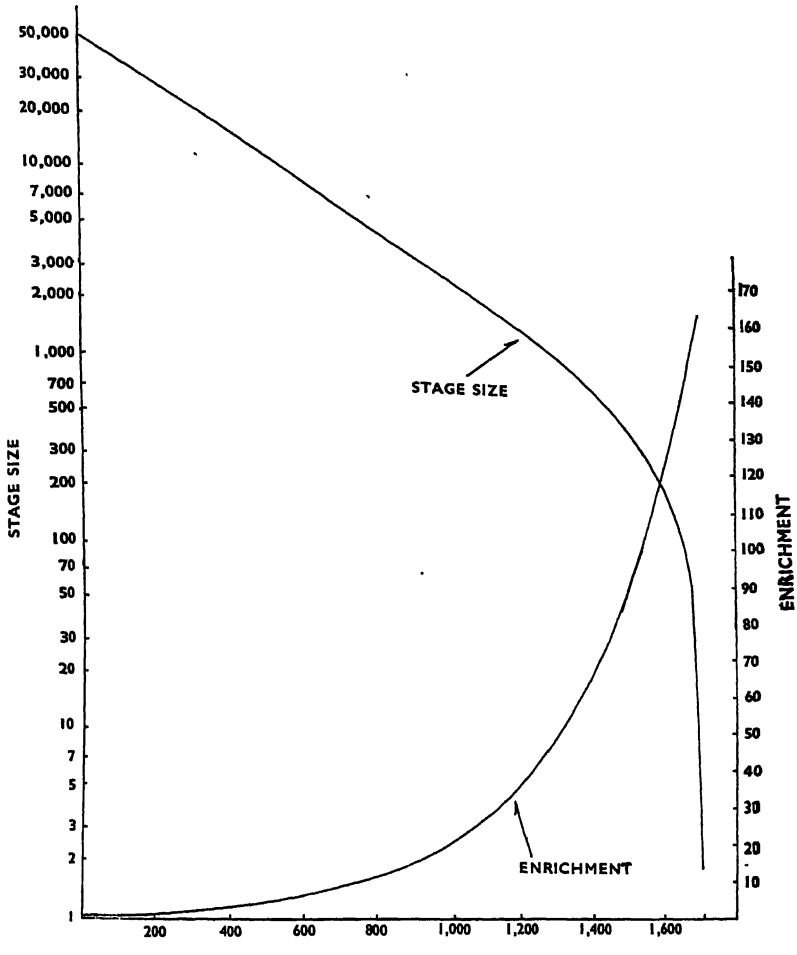


**Fig. 38.** Enrichment and stage size throughout uranium diffusion plant.

is also a curve showing the enrichment of the material used in any stage of the plant.

It will be realized that the numerical values are theoretical ones, appropriate to an ideal diffusion plant. In actual practice, adjustments must be made to allow for the properties of the apparatus which is to be employed. It is to be expected, however, that such changes will not require any great departure from these general conclusions relating to an ideal diffusion cascade.

(4) *Some features of a diffusion plant.*

It is of interest to consider briefly some practical details of a diffusion plant and to examine, in particular, the type of porous membrane required and the apparatus needed to pass the gas from stage to stage. According to the information published, it was proposed to take gas at atmospheric pressure and to allow it to diffuse through a porous membrane into a region where the pressure was maintained at about 0.1 atmosphere. To obtain the highest possible enrichment factor per stage, it was necessary to use a membrane with very small holes in it, and in order to diffuse gas rapidly through this membrane very many holes were required. It was necessary to use membranes which were not attacked by the diffusing gas and in which the tiny holes of less than $10^{-6}$ cm. diameter neither clogged nor enlarged with use. Added to these very severe requirements was the need for using a membrane structure with sufficient strength to withstand a pressure difference of 1 atmosphere. For a large scale plant many acres of this type of porous membrane are required. The plant requires many pumps, not only to compress the diffused gas from 0.1 atmosphere to 1 atmosphere at which pressure it enters the next higher stage, but also to raise the pressure of the impoverished gas and to convey it to the stage below. It was essential that these pumps, numbering some thousands, should neither leak nor corrode, and this also was a requirement of the whole of the gas circulating system. The problem of connecting miles of piping in such a way that there are no leaks, is one to which there is no simple solution. It is necessary to have reliable workmen to connect the pipes, using the best possible methods of making joints, and then to ascertain whether any leaks exist and if so to find them. To-day, this is practicable, even on a large scale; the task of finding leaks has been made much easier by a new method of leak detection in which a simple mass spectrograph is used to look for the presence, inside the apparatus, of a suitable testing gas to which a suspected leak is exposed. When the diffusion plant is free from leaks, $U^{235}$ will be lost only because of chemical action between the working gas and materials within the system, or because discarded impoverished material contains appreciable quantities of $U^{235}$. The structure of the plant was such as to avoid corrosion of the metal forming the gas

circulating system, and to provide negligible opportunities for reactions between uranium hexafluoride and materials which were used to make vacuum tight seals in various parts of the equipment; consequently the main loss arose because of the $U^{235}$ content of the output from the stripping cascade.

The diagram of the diffusion cascade process shows the equilibrium state when the material taken into the plant is equal to the output. When the plant is started up, however, the only material available is $UF_6$ made from natural uranium, and of necessity the operation of the plant commences with the use of only the input stage. Each stage of the plant requires a finite amount of gas to enable operation to occur at all, and for this reason the plant must work for a long period before all the stages are in operation. Only after the elapse of a considerable time has enough enriched material accumulated to allow the operation of the higher stages of the plant, and for this reason there is a start up period in which there is no output although material is continuously entering the diffusion plant. Another aspect of this property of the diffusion plant is the necessity for having locked up within it large quantities of uranium hexafluoride, some small fraction of which is very considerably enriched. The provision of this working material is an essential requirement, and during a continuous process it represents a stock of uranium hexafluoride from which no $U^{235}$ is obtained. The disadvantages of having a large stock of working material in the early stages of the plant are not particularly serious, for, although the bulk of the locked up material is actually in these stages, it has not been greatly enriched. On the other hand, in a plant using 4000 stages to prepare 99.3% $U^{235}$, 2000 stages are required to convert 50% $U^{235}$ into the desired product, and the holding up of such valuable working material within these stages is a great disadvantage. Despite the suitability of the diffusion plant for the large scale handling of material containing low concentrations of $U^{235}$, it is possible that a different method, involving the holding up of smaller quantities of enriched material, is desirable for the final concentration processes. The inconvenience of the delay in obtaining output and the large stock of material held inside the plant are necessary consequences of a process in which there is only a small enrichment factor per stage. To minimize these disadvantages, the diffusion plant must be designed so as to reduce, as far as practicable, the amount of material required for the operation of a single unit of the plant.

This brief description of the diffusion plant gives an inadequate picture of the difficulties of putting it into operation. Construction of the plant at Oak Ridge, Tennessee, was commenced in the summer of 1943 but it was not until early in 1945 that the immense plant was in successful operation. A photograph of the exterior of the plant is shown in Fig. 39. Rumour had it that the Manhattan District Engineers had great faith in the diffusion plant,

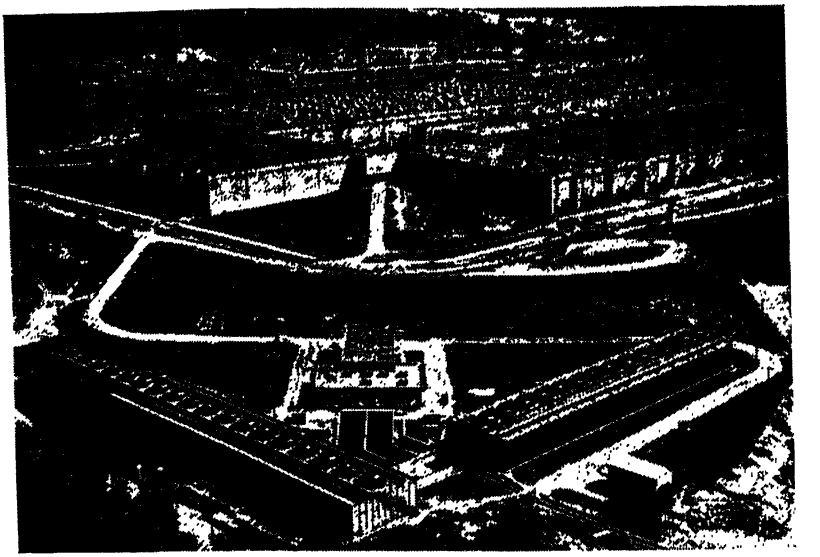

**Fig. 39.** The porous barrier diffusion plant at Oak Ridge, Tennessee.
(Reproduced by courtesy of the War Department, U.S.A.)

that an eminent scientist had given his opinion that the plant would not work, and that in fact there were superhuman difficulties to be overcome before it would work. At length the rumours ceased. It was known that the diffusion plant was working, although, of course, no details were available. From official statements made since the end of the war, it is apparent that the diffusion plant is the most satisfactory and economical means of separating the isotopes of uranium, and that this separation plant alone is to be kept in operation in times of peace. Its performance justifies the confidence of the Manhattan District Engineers and of those British physicists who also were convinced of the feasibility of using a diffusion plant to separate the uranium isotopes.

(5) *Electromagnetic separation method.*

Although the diffusion process has been so successful, the first supplies of fissionable material were produced by a different method which in principle and in operation is just a mass spectrograph. As has long been realized, if

a mass spectrograph will distinguish isotopes and give their masses, it will also permit their separation. This method was used many years ago by Oliphant[3] to separate the lithium isotopes $Li^6$ and $Li^7$, and it was used more recently by Nier[4] to separate the uranium isotopes. The main difficulty in using it, even for small scale separations, is that of devising a satisfactory means for transforming the material being handled into atoms carrying single positive charges, or, as they would normally be described, into singly charged or monovalent ions. In previous isotope separations using the electromagnetic method, the ion beams were minute and the yield of pure isotopes was measured in micrograms ($10^{-6}$g.).

The Faraday, the amount of electricity which in electrolysis transports 1 g. equivalent of a substance, is the rather large charge of $9.65 \times 10^4$ coulombs. This means that if we can readily produce uranium ions in a mass spectrograph, we shall require to pass, for example, an ion current of 1 ampere for 27 hours in order to transport 238 g. of uranium, and of this only about 1.7 g. is $U^{235}$. A mass spectrograph, kept working continuously with a current of 1 amp. of mixed uranium monovalent ions would require a period of nearly two years to separate 1 kg. of $U^{235}$. A calculation of this type shows that this method of isotope separation is impracticable on any adequate scale unless it is possible to build mass spectrographs of such size or in such numbers that they provide a total uranium ion current of about 100 amp. In Nier's experiments, in which he used a mass spectrograph to obtain small quantities of $U^{235}$, the ion current was less than 1 microamp.

(6) *General arrangements of the electromagnetic method.*

In Berkeley, California, the small cyclotron was dismantled in the autumn of 1941 and the magnet, which gave a uniform field between 37″ diameter pole pieces, was used for experiments on the separation of uranium ions. It was proposed to arrange a strong electron beam passing in the direction of the magnetic field. Through this beam was to diffuse the vapour of a salt of uranium so that there was decomposition and ionization of the vapour; accelerating electrodes in the neighbourhood of the electron beam were to be maintained at a high negative potential with respect to the beam so as to accelerate positive ions which diffused from the region traversed by the electrons. Although success was finally achieved, there were at first some obvious sources of difficulty. Would it prove possible to obtain strong beams of uranium ions, and if so would the electrostatic forces of repulsion between the ions in the beam be strong enough to disperse the beam and make it impossible to obtain a separation of the uranium isotopes? Further-

more, was it possible to arrange that a reasonable fraction of the ions drawn from the ion source consisted of monovalent uranium ions ?

Let us consider some of these points briefly and in doing so examine some general features of the method. In Fig. 40 is a plan of the arrangements between the poles of the magnet; it is assumed that the magnetic flux is upwards and at right angles to the plane of the diagram. The ions from the source S, which was of the nature mentioned above, are accelerated by suitable

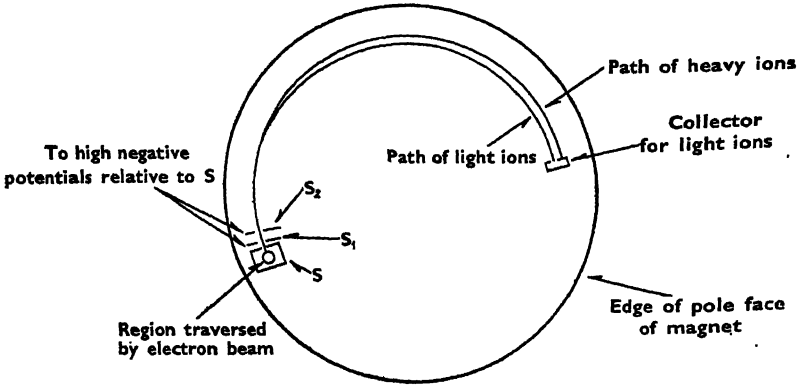


**Fig. 40.** Plan showing the arrangement for electromagnetic separation.

potentials and pass through slits $S_1$ and $S_2$; the methods of electron focussing of beams for cathode ray tubes indicate the arrangements of distances and potentials which are likely to give a well focussed beam. Suppose that ions of mass m, carrying the electronic charge e, fall through a total potential V. Then their velocity is $\sqrt{\frac{2Ve}{m}}$ and the radius of curvature of the path they describe in a magnetic field of induction B is $\frac{1}{B}\sqrt{\frac{2Vm}{e}}$ *. In practice the ions are allowed to describe semicircles; the diameters of these will be proportional to the square roots of the masses of the ions; in the case of the isotopes of uranium the diameter of the $U^{235}$ ion path is about 0.6% less than that of the $U^{238}$ ions. If these paths are described in the field of an electromagnet with a pole diameter of 37", the greatest possible separation of the two beams is less than 6 mm.

This shows that the separation of uranium isotopes will be possible only

* These relations are easily derived. This is done in Appendix I, p. 182.

with beams which can be brought to a focus with a width of a few millimetres, and, as may be shown from theory, or indirectly from experience with the beams of cathode ray tubes, it does not appear possible to obtain good focus with a beam 1·5 metres in length unless it carries only a small current. It was considered, however, that conditions might be made more favourable by the magnetic field which seriously restricts the motion of slow ions or electrons, and it was found in fact that in some circumstances positive ion beams in a magnetic field are not subject to undue spread from mutual repulsion of the ions in them, a result that must be attributed to the presence of negatively charged particles within the region traversed by the beam, and to the consequent existence of attractive forces which hold the beam together. Because of this fortunate circumstance, it proved possible to obtain well focussed ion beams of much greater current densities than had been anticipated, but in order to achieve the best results it was necessary to use high potentials for accelerating the ions.

The final choice of accelerating voltage will depend upon many factors, of which some are economic, but it seems reasonable to say that voltages should not be lower than 20 kV and will not be much higher than 50 kV. Uranium ions which have been accelerated by 20 kV describe a circle of radius 0.5 metres in a field of about 0.6 webers per metre$^2$ (6000 gauss), a field which though high is not to be considered unreasonably difficult to provide. Nevertheless, this simple calculation gives some indication of the magnitude of the problem which was to be solved, for even if all the ions from the ion source were uranium ions—and actual experience was far less favourable than this—it was necessary to make available apparatus to deliver the order of 100 amperes at a potential of 20 kV or more and to provide strong magnetic fields in large evacuated tanks in which these beams described their paths. If the separation method was to be successful, it was further necessary to arrange a high degree of constancy of both the magnetic field and the accelerating voltage; deviations of more than a very few parts in one thousand could not be tolerated.

These difficulties were in fact rather more serious than can be indicated here, but they were far less troublesome than those arising from attempts to obtain ion beams carrying large currents. It was necessary, among other things, to arrange the apparatus so as to make use of rather divergent beams from the ion source, but it was essential that the use of wider beams should not cause any marked deterioration of the focus. Fortunately, a device employing a localized ion source to produce ions which have a semicircular path in a magnetic field is well adapted to the use of wide beams; this can be shown by drawing several circles of the same radius with neighbouring

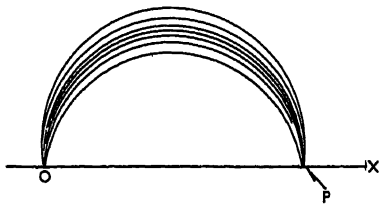


**Fig. 41.** A divergent beam from O describes a circular path of constant diameter OP and focusses close to P.

centres and with one point O in common. This has been done in Fig. 41 where it is seen that all these circles cut the line OX at points which are quite close together. If these circles represent ion paths, a receiver placed near the point P will collect almost all the ions from the rather divergent beam arising from the point O. The quality of focus can be somewhat improved, for a given beam divergence, by using a magnetic field which, instead of being uniform, has spatial variations of the correct form. Although the use of such a field is of real advantage, it is still the case, just as is seen in Fig. 41, that some ions meet the line OX rather closer to O than is desired. This is particularly unfortunate, for if the diagram represents the paths of $U^{238}$ ions the $U^{235}$ collector is on the side of P nearer O just where unwanted ions, that form the tail of the $U^{238}$ beam, will fall into it. Clearly, the divergence of the beam can be reduced if desired, and if this is done, the product $U^{235}$ will be purer in quality and smaller in amount; it is essential to preserve the proper balance between large yield and high purity. The enrichment factor achieved by this method is very high, but as it is certainly not sufficiently high to give a suitable product in one stage, it is possible to arrange to obtain large yields in the first stage and high purity in the subsequent one.

(7) *Advantages and disadvantages of the electromagnetic method.*

The electromagnetic method has many desirable features, particularly that of making use of a considerable number of independent units, each of which consists of a high voltage supply and control unit, together with a source of ions and a collector in a vacuum tank through which passed the necessary magnetic field. The operating plant was set up in Oak Ridge, Tennessee, and made use of ion sources and collectors developed in the Radiation Laboratory of the University of California. Fig. 42 is a photograph of a portion of the electromagnetic separation plant. Because of the smallness of the units into which the plant was divided, it was possible to continue development of the separation processes during the running of the plant; improvements which were decided upon were thus available from time to time, and when conditions suited these improvements were quickly put into use. These features of the apparatus used in the electromagnetic plant were of the greatest advantage in the circumstances which existed at the beginning of 1944, when it was urgently necessary to obtain appreciable supplies of reasonably pure $U^{235}$.

On the other hand, the apparatus was complicated and expensive, and required skilled personnel for its operation. The most serious objection to the method arises because only a small fraction of the uranium in the ion

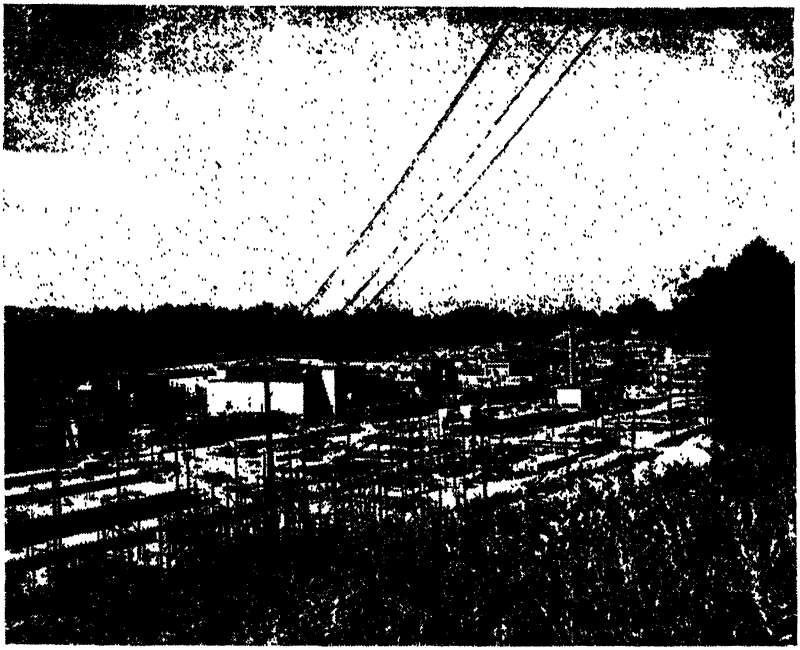

**Fig. 42.** A portion of the electromagnetic separation plant at Oak Ridge, Tennessee.
(Reproduced by courtesy of the War Department, U.S.A.)

source actually finds its way into the ion beam; the remainder, which deposits itself on various parts of the vacuum system within which the separation process is carried out, has to be collected from time to time and re-treated chemically for subsequent use. This feature of the process, and the complication of the necessary chemical treatments, bring about a greater hold up of material than might have been anticipated; in addition, it is essential, especially when using material with high $U^{235}$ concentrations, to take the greatest precautions to avoid loss. It is probable that the electromagnetic

separation method is best suited for small amounts of material; if its use is justified in the process of separating the uranium isotopes, it will be in conjunction with the diffusion process which is best suited for handling large amounts of material and for achieving an initial enrichment which provides a suitable material for final treatment by the electromagnetic method.

Of the atomic bombs which were dropped on Japan, the Hiroshima bomb, it is said, made use of $U^{235}$. The separation of the necessary material depended upon both the diffusion plant and the electromagnetic method; it is reasonable to suppose that the existence of the necessary quantity of $U^{235}$ depended in no small measure upon the success of the electromagnetic separation method. Whatever the truth of this surmise, it is certain that the electromagnetic method made available the first substantial supplies of fissionable material. In view of the very small yields obtained from pre-war attempts to separate isotopes by the electromagnetic method, the successes achieved in Berkeley and in large scale operation in Oak Ridge, Tennessee, are most remarkable. They serve to remind us again of what scientists can accomplish by team work where the leadership is of high quality and adequate facilities are available for the tasks in hand.

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[2] Smyth Report, 9.9.
[3] Oliphant, Shire and Crowther, Proc. Roy. Soc., A 146, 922, 1934.
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## CHAPTER XV

# ATOMIC ENERGY AND THE FUTURE

(1) *Future organization of scientific research work.*

It is natural to contrast the manner in which scientific problems have been solved during peace and war. In peace time, fundamental scientific discoveries originated partly from the efforts of a few leaders and their assistants and partly from very small scale experiments which were carried out elsewhere by a relatively large number of individuals. It had always been maintained that the most fertile soil in which fundamental scientific theories grow is that of freedom for the individual to investigate what interests him. It is true that the problems of the atomic bomb were concerned only in part with fundamentals, but it is certain that these problems were solved, not by many individuals investigating whatever interested them, but by wise leadership which directed the work of very large teams of capable scientists. They worked hard because they were convinced of the value and importance of their work, and success was achieved because every effort was directed towards a single goal.

In normal circumstances the scientist is a cooperative individual, for he likes to discuss with others his ideas and his experiments; in the abnormal circumstances of war time research on atomic energy, cooperation was greatly extended by frequent discussion meetings in which day to day results were set forth by the individual workers who were carrying out experiments. Good suggestions were welcome from whatever source. The scientist had not forgotten his individualism; success in his own problem was still a spur to his efforts but he realized, too, that the success of the atomic bomb was of greater importance. If his work was not making a positive contribution to the atomic bomb he realized that there was every justification for stopping it. If ever the truth is told it will be found that in the atomic bomb project much work was wasted; investigations were stopped, not because they were leading nowhere, but because they were unlikely to contribute much to the immediate objective, that of making an atomic bomb.

Success itself must not delude us into the belief that the organization of the atomic bomb project is representative of the correct way to do all research work, nor should the novelty of the organization prejudice us against it. If we consider the Los Alamos group alone, we find that its successes arose in part because there existed there a physics research laboratory which Smyth

claims, apparently with justice, to have been the best equipped in the world. In addition, in the laboratory were grouped together some of the ablest scientists in the world. Success was achieved because of the enthusiasm and ability of the workers and the facilities at their disposal. It would appear likely that in similar conditions science can achieve in peace time just as much as has been achieved in atomic bomb research during the war. Scientific research work in the near future must, similarly, be carried out by teams of enthusiastic workers, well led and having at their disposal adequate facilities for their work. This will cost money, but money spent on investigating the right problems may return dividends which are enormous in proportion to the expenditure made. The development of atomic energy is a case in point; in peace time this can hardly hope to develop at quite the rate achieved during war, but it can be developed rapidly if the countries interested are prepared to devote the necessary resources to the work. Expensive apparatus and a considerable staff of competent scientists will be required, but the mere spending of money on these things will not achieve results quickly. Even the scientist is human, and he will not work with the enthusiasm that can be so productive unless the support his work receives is such as to convince him that the Government for which he works is in real earnest in its desire to push ahead with the development of atomic energy. If the proper steps are taken we may see great progress in this field during the next five to ten years.

(2) *Atomic bombs in war.*

Unfortunately, however, there are other possibilities. Without the slightest doubt, the atomic bomb is an ideal weapon of aggression. A few bombs, discharged on vital places in Britain, would give rise to such destruction that this country would have little or no prospect of waging a successful war. It is sometimes assumed that in the next war atomic bombs will not be used because of their great destructive power; this view is supported by the argument that in somewhat similar circumstances poison gas was not used in the recent war. It is probable, however, that possessors of atomic bombs will use them if there appears, on balance, to be real advantage in doing so, especially since the Allies used them against Japan; it is hardly to be expected that any future enemy of ours will hesitate before raining atomic bombs on this country or even on the United States of America if by doing so the success of his arms seems likely to be more quickly assured. Thus, the most sensible assumption is that atomic bombs are certain to be used in any future war and so the efforts of statesmen must be directed towards preventing war rather than towards making international laws which, even if observed, would only make wars a little less destructive and unpleasant. The only possible

alternative—and in fact this is not practicable—is that of ensuring that no possible enemy possesses atomic bombs.

Now unfortunately, there is no real hope that the present state of affairs, in which the U.S.A. is the sole possessor of atomic bombs or of fissionable material, can continue for long. Great Britain, which has cooperated with the U.S.A. in the development of the atomic bomb, intends to carry out investigations of atomic energy, and for this purpose it will be necessary to manufacture plutonium and perhaps also $U^{235}$; the experiments carried out will make available supplies of the materials which are suitable for producing atomic bombs and so it will be very difficult for other countries to be certain whether atomic energy experiments are directed primarily towards the development of sources of industrial power or towards the accumulation of atomic bombs or of the material from which to make them. This country would show an undue confidence in the prospects of avoiding future war if it failed to take reasonable precautions for securing a supply of the material from which atomic bombs may be made.

What is reasonable for us is just as reasonable for others, and there can be no doubt that many powers, great and not so great, will consider that they can only insure future freedom to develop as they wish if they too possess supplies of atomic bombs. It is doubtful whether the countries of the world would agree not to make atomic bombs, but even if they did so the menace of the atomic bomb would be but slightly reduced, for as long as a country can make or separate fissionable material for experiments on atomic energy, that country will not have much difficulty in making atomic bombs.

Now the technical processes used in separating uranium isotopes or in arranging for the manufacture and extraction of plutonium are costly and difficult, and it is true that the Americans, with perhaps the British and the Canadians, have knowledge and experience of these methods that is denied to other nations; in this respect the U.S.A. particularly has a favourable position. Nevertheless, as the Allied atomic bomb project was successful in achieving the atomic bomb without prior experimental proof of its practicability, other nations who wish to make atomic bombs or to develop atomic energy will at the worst be more favourably situated than were the Allies in 1939, and for this reason the present Allied or American monopoly must be regarded as unlikely to endure. There is no use in an agreement not to make atomic bombs, unless there is also an agreement to make no fissionable material; but then the development of atomic energy would be tremendously retarded if such an agreement were observed, and doubtless a proposal for it would receive negligible support. Progress in the development of atomic energy is likely to mean progress in the size and destructiveness of atomic

bombs, and the only real hope for civilization lies in appreciating that technical progress in this and in other spheres makes war much more destructive; the only way of avoiding destruction is to have no war, and this endeavour, not the making of rules in an attempt to control the use of atomic bombs, must be the ultimate purpose of statesmanship to-day.

There is another difficulty of a more obvious type. If it proves possible to use plutonium or $U^{235}$ as a source of power in engines, it means that these materials will find their way into the hands of an appreciable number of people. Can precautions be taken to prevent some of these people pooling their supplies to make an atomic bomb? This matter has recently been discussed publicly, and it has been made clear that a safeguard is easily available. It will be appreciated that although nearly pure $U^{235}$ is essential for an atomic bomb, even natural uranium can be used in a very large pile and so samples of uranium with about 50% $U^{235}$ would make possible the release of atomic energy in a controlled reacting pile of reasonable size, even though this material would be quite unsuitable for use in an atomic bomb. Doubtless it could be made to explode, but as the material would not permit the development of a fast-growing chain reaction the explosion would only be comparable with those produced by ordinary means. Consequently, for such atomic energy processes as may prove feasible, uranium in which the proportion of $U^{235}$ is ten to one hundred times that occurring in natural uranium may be entirely satisfactory for every possible process except that of making atomic bombs. There would then be no objection to the widespread distribution of such material, unless it was thought that it was likely to be used as the raw material for a plant that was preparing pure $U^{235}$. From the statements which have been made, it is apparent that it is also possible to combine with $Pu^{239}$ a plutonium isotope which ensures that the mixture is useless for making atomic bombs. Details of the source or mass number of this isotope do not appear to have been released. It is clear, however, that, in the same way as in the case of uranium, such a mixture of plutonium isotopes may be eminently satisfactory for the production of atomic power in a controlled chain reaction, despite its inability to give a fast-growing chain reaction in an atomic bomb.

(3) *Atomic energy for small power plants.*

Let us try to decide what peaceful uses can now be made of atomic energy. There is no doubt that $U^{235}$ and $Pu^{239}$ are capable of being used to develop heat energy as a result of a controlled chain reaction. The arrangements required to achieve this are fairly clear, at any rate in outline; the active material should be used with a moderator so as to lengthen the life time of a generation of neutrons and to slow them down to speeds at which they are

most likely to be captured. Provision must be made for the use of neutron-absorbing rods so as to make it possible to maintain the reaction, and the power output, at the desired level, and these should be automatically controlled. In very many respects the unit which develops atomic energy from $U^{235}$ or from $Pu^{239}$ is like an atomic pile designed for the use of natural uranium, although, of course, it is not essential here to use a lattice structure in which the uranium is concentrated in a number of discrete masses immersed in a large volume of moderator; furthermore the structure will be much smaller than the type of atomic pile used for the manufacture of plutonium. It seems likely, however, that it will be larger than an atomic bomb, even though it contains less active material.

Many people have been led to believe that the day may come when plutonium power units will be built into motor cars, but if present estimates are at all accurate this is most unlikely. If such an arrangement were possible it would present the fuel problem in a novel form; for the fuel would be purchased with the car and it is likely that what remained of it would still be of great value after the car was mechanically useless. If we estimate the running life of a car as being 5000 hours and assume that it develops 40 kW, we find that in all it develops $2 \times 10^5$ kWh, the amount of energy which is released by the fission of 8 g. of uranium; hence this is the quantity of $Pu^{239}$ or $U^{235}$ which would be consumed during the life of the car and small though this amount is, it is likely to be expensive. It is probable, too, that many times this quantity of material will have to be carried in order to achieve the necessary liberation of atomic energy. Now although these difficulties may prove to involve serious financial problems, there are technical difficulties which are even more troublesome. In the first place there is the emission of radiation which accompanies the operation of a pile; although a motor car power unit is a small one, the assumed power production level is associated with radiation comparable with that from 40 kg. of radium, and provision must be made to protect the driver and his passengers from such intense radiations. This can be achieved by surrounding the source of atomic power by a sufficient thickness of concrete, the actual thickness depending upon the precise properties of the radiations emitted; but unless these radiations are much less penetrating than those from radium, it appears that the necessary thickness of concrete is not less than 6ft. The advantages of an atomic energy motor car fade away when it is found that its use involves encasing the source of power in so large a sphere of concrete, the inconvenient shape and size of which are more acceptable than the mass, which exceeds 50 tons.

If atomic energy units are not suitable for driving motor cars, can they be used in railway locomotives or on board ships? Here the prospects are

better. In the case of a railway locomotive, weight within reason is an actual advantage, and the possibility of placing the power unit at a considerable distance from the engine driver and of surrounding it with a large mass of concrete or of other absorber of radiation does not seem to be unreasonable. Even here, however, there are problems to be overcome. The fission products must not be allowed to escape, or there will be serious dangers of radioactive poisoning from these materials. Furthermore the satisfactory performance of this source of atomic power depends on the effects, on the controlled chain reaction, of the fission products which are produced as atomic power is released. If these materials absorb neutrons, and are produced in sufficient quantities, there will be difficulties in maintaining the chain reaction, and the liberation of power may cease.

This brief review of the feasibility of using plutonium in relatively small scale power units is speculative and it is subject to modification as more information becomes available. It does seem reasonable to suppose, however, that a locomotive or a steamship could be driven by heat from a small atomic energy unit, but the means for achieving this will require to be examined and it will be necessary to test and perfect any arrangement that appears to have good prospects of success. The technical problem is not by any means the only one; atomic energy will not be used widely in the way suggested unless it is economically attractive, but this cannot finally be determined until the relevant technical problems have been solved.

(4) *Atomic energy for large electrical generating stations.*

It will be appreciated that atomic piles like those at Hanford liberate very large amounts of heat energy, and it appears possible that use can be made of some of it. It will be remembered that this heat is liberated in the uranium slugs from which it is conducted to some cooling fluid; in the case of a pile operated for the production of plutonium it has been arranged to keep the uranium slugs at a relatively low temperature. On the other hand, the requirements of a pile operated for power production are those dictated by the thermodynamics of heat engines; considerations which are well known and which arise indirectly from the second law of thermodynamics, show that the greatest efficiency results if the source of heat is at the highest possible temperature. Hence, if the atomic pile is to liberate energy to be used in heat engines for the production, for example, of electrical power, the uranium slugs must be operated at a high temperature and the heat developed within them must be transferred at a comparable temperature to the working fluid of the heat engine. When account is taken of the processes occurring within a pile, it is evident that the problem of making efficient use of the heat energy liberated is one that may not be simple to solve, although, in view of the

difficulties which have already been overcome in connection with the development of atomic energy, it is likely that a satisfactory arrangement will eventually be devised.

It would appear also that the possibility of using an atomic pile as a source of heat will depend largely on the time for which the pile will run without replacing the uranium slugs. If it turns out that the fission products soon accumulate to a sufficient extent to absorb many neutrons and stop the operation of the pile, it will be necessary to remove the uranium and extract the fission products by chemical treatment long before the fissionable material within the uranium is so greatly depleted as to make it useless for the liberation of atomic energy. This may prove a serious disadvantage, in view of the difficult nature of the necessary chemical processes. It is rather unfortunate that we cannot see any way of using atomic energy except by allowing the fission energy to be converted into heat and then using it in relatively inefficient heat engines. Initially the greater part of the fission energy exists in the electrical repulsion of the two fission fragments; subsequently it is transformed into heat energy, and of this only a portion can be converted into mechanical or electrical energy for industrial uses.

What has been written already in this chapter assumes that the separation of $U^{235}$ from natural uranium will continue to be a difficult and expensive process. Although such an assumption appears to be justified, we should not overlook the consequences that would arise if a simple, cheap and efficient method of isotope separation were devised. On the one hand, the difficulty of producing atomic bombs would largely disappear; if the necessary raw material was available, they might be no more troublesome to produce than motor cars, and any nation which was favoured by the possession of uranium supplies would be able to build up stocks of atomic bombs. On the other hand, the liberation of atomic power could then be effected by using uranium which had been enriched in $U^{235}$ as described in the section above, with advantages of economy and convenience over the alternative of using larger piles operating on natural uranium. In some cases the use of pure $U^{235}$ might be advantageous, although it will be appreciated that some admixture of $U^{238}$ is usually desirable. Not only does this prevent the occurrence of a fast-growing chain reaction, but it results in conversion of $U^{238}$ into fissionable material; for reasons of economy it is better to capture neutrons in $U^{238}$—or in $Th^{232}$*—than to allow them to leave the pile or be absorbed uselessly.

(5) *Uranium supplies.*

In connection with the future of atomic energy a very important question is the availability of uranium. In terms of present knowledge, it will not be

* See footnote, Chap. XI, p. 112.

useful to contemplate the large scale use of atomic energy unless there are large supplies of uranium which can readily be obtained. The magnitude of workable uranium deposits is a matter of some doubt. In order to obtain some idea of the quantities required annually, let us consider what would be involved if the whole electrical supply of Great Britain was generated from heat liberated in uranium fission. The public supply of electricity provides, on the average, 5 million kW, or 120 million kWh daily. This is the amount of energy liberated on the fission of about 12 lb. of uranium; of course this heat energy would not yield so much electrical power; losses, and the low thermodynamic efficiency of a heat engine, would result in giving in the form of electrical energy only about $\frac{1}{3}$ of that liberated in fission. Nevertheless, the amount of $U^{235}$ necessary to produce the total electrical supply for this country is amazingly small, for it requires the consumption of some six tons of fissionable uranium annually. In practice, it is not likely to be economically profitable to extract $U^{235}$ from natural uranium, and it is consequently necessary to contemplate making use of natural uranium; however this may be, the natural uranium requirement is found to be about 1000 tons a year, provided that use is made of the whole $U^{235}$ content of uranium. To achieve so much is unlikely, so that we estimate the uranium requirements at a few thousand tons annually for the production of the electric power at present generated by the public supply, and perhaps a few tens of thousands of tons annually for the amount of electric power that must be used here if we are to remain a great manufacturing nation. Regarded even from the point of view of world consumption, the amounts required are small compared with world consumptions of coal, steel, and many metals of commerce. The mining of this uranium is not a major task, provided that it occurs in sufficient amount in rich deposits.

Estimates based on knowledge of the size of known high grade uranium deposits appear to discourage the belief that there is sufficient uranium available for long term power production on a large scale,* but against this we must remember that uranium has not heretofore been regarded as a valuable mineral for which intensive prospecting was justified. Uranium is widely distributed in small amounts throughout the rocks found on the surface of the earth, and it may well be that the new interest in uranium will lead to the discovery of large new sources of supply. Indeed, this may have occurred already; information concerning new uranium deposits is regarded as a military secret, and details of success or failure in locating useful deposits are not at present available.

It is clear that there are important problems—technical, geological and eco-

* Those known prior to 1939 have been estimated to amount to 50,000 tons of natural uranium[1].

nomic—to be solved before atomic energy can be used on any large scale for providing industrial power. There seem to be good prospects of overcoming the difficulties they present and possibly this can be done fairly quickly if sufficient effort is applied. Although this country was early in the field of the development of atomic energy, the circumstances of the war have led to such a great relative advancement in the U.S.A. that a particularly large effort will be required here if British inventiveness is to play, in the development of atomic energy, the part which is commensurate with its capabilities.

Unfortunately, the development of nuclear physics, which is fundamental to advances in methods of using atomic energy, is greatly handicapped by the lack of information concerning experimental work carried out during the war, principally in the Los Alamos laboratories. Smyth mentions that the store of knowledge accumulated by the Los Alamos Experimental Nuclear Physics Division forms an integral and invaluable part of all thinking on nuclear problems[2]; it is to be regretted that considerations of military security should delay the free publication of such material. The knowledge of nature contained in the reports of this division cannot long be secret, but until these reports are published or the data they contain are redetermined and made known to the scientific world, the progress of nuclear physics is unnecessarily impeded.

(6) *The use of atomic energy processes for making artificial radioactive substances.*

Whatever success is achieved in attempts to use atomic energy as a source of industrial power, there is one respect in which progress in atomic energy is almost certain to have most beneficial results. In the discussion of the nature of an atomic pile, it was pointed out that within a pile there were sufficient neutrons to bring about alterations in the properties of matter which was subjected to their bombardment. Although the number of neutrons per unit volume in a pile is very small compared with the number of atoms per unit volume of a gas at normal temperature and pressure, yet the number of neutrons passing per second through a cm.$^2$ of the area of the pile is much greater than the number released by any possible laboratory neutron source and consequently, in some cases, the uranium pile makes possible neutron experiments that cannot be carried out in the laboratory. Small samples of material, placed within a pile, are subject to most intense neutron bombardment, and in certain cases where neutron capture occurs, a small portion of these substances will be transformed into an isotope of the material being bombarded. We see an example of the advantage of the use of a pile for such a purpose, when we compare the rate of production of $Pu^{239}$ using neutrons from a cyclotron and using those in a pile. This of course is an

extreme case, but it is generally true that nuclear processes which are brought about by neutron bombardment can be performed on a far larger scale by the use of a pile than by using any neutron source.

Now the importance of these neutron-induced nuclear transformations lies in the field of medicine. A simple example is provided by an experiment in which animals—in the case considered they were rats—were given food containing artificial radioactive phosphorus. From the point of view of the animal accepting the food, radio-phosphorus does not differ from ordinary phosphorus, $P^{31}$; it is true that radio-phosphorus has mass number 32, but this makes no appreciable difference to its chemical properties, to its taste or ease of digestion; it is also true that the phosphorus is radioactive, but by the time it has exhibited this property it is no longer phosphorus. Now $P^{32}_{15}$ has the convenient half life of 14.5 days; if an animal is given a meal containing some radio-phosphorus, it can be killed subsequently and the various parts of its body subjected to analysis. The point of interest in such an experiment is the general problem of phosphorus metabolism; how much of the phosphorus of the meal was retained in the body structure of the animal and of this portion what fraction entered the teeth, the bones and other phosphorus-containing organs? Naturally, as the radio-phosphorus behaves just like ordinary phosphorus, the history of the phosphorus of that particular meal is shown by the location of the radio-phosphorus. This phosphorus is distinguishable from ordinary phosphorus because of its higher mass number, and if it had been absorbed in some quantity it could be detected even if it were not radioactive. But as this isotope is radioactive, it is possible to detect it even though it is present only in minute amounts, and in practice a relatively small dose of radioactive phosphorus is sufficient to allow its fate to be followed with adequate accuracy. Experiments of this type have shown that the phosphorus of a rat's teeth is slowly but regularly replaced by some of the phosphorus taken in daily. This discovery, which was a surprising one, could hardly have been made without the use of radioactive phosphorus, a substance which can be produced in several ways, including the bombardment of $P^{31}$ by neutrons.

Phosphorus is only one of the elements which play an important part in metabolism; there are other elements which are needed in some considerable quantity and in addition there are elements such as iron, manganese and copper which are essential but are required only in small amounts. Information concerning their metabolism is of considerable interest, and can best be obtained from animal experiments using food which contains small quantities of radioactive forms of these elements. In most cases adequate quantities of radioactive forms of common elements can readily be produced by

## APPENDIX I

# METHODS FOR ACCELERATING CHARGED PARTICLES

From about 1925 onwards there was a growing realization that nuclear physics would make a notable advance if it were possible to devise means of accelerating charged particles. Up to that time the only fast particles available were $\alpha$ particles with energies of up to about 8 MeV; such particles were useful but they were not available in sufficient numbers or indeed with sufficient energy. It was not usually possible to employ a source of particles which supplied more than $3 \times 10^9$ $\alpha$ particles a second and as each of these carries two positive charges its ability to approach closely to a nucleus is seriously limited. Nevertheless it was difficult to find any practicable alternative. There was the possibility of using the positive ions that are present in a discharge tube; these exist in vast numbers, but in the discharge tube itself they have very low energies and it is necessary to devise means for accelerating them if they are to be of use in effecting nuclear transformations.

It should be realized that the generation and use of high electrical potentials is a most difficult problem. Potential differences of 10 kV are very easy to generate, a potential of 100 kV is much more difficult, and one of 1000kV or more can be generated and employed only when very elaborate precautions are taken. Such voltages will spark over long distances because under the influence of very powerful electric fields air is no longer an insulator. It was apparent that although these high voltages would provide direct means of accelerating positive ions, it was not likely that they could be used to provide ions with energies in excess of a very few MeV.

Cockcroft and Walton used this direct method for accelerating hydrogen ions, and with it they succeeded in disintegrating lithium. This nuclear transformation, and a few others, including the D on D reaction, can be carried out by ions with energies less than 1 MeV, but these reactions are exceptional, and usually much higher energies are required. There is little advantage in considering the details of these direct methods of accelerating charged particles; the problems are those of obtaining the necessary steady high voltages and of designing an accelerating tube to which they can safely be applied. This method is useful in reactions which require the use of low energy particles, but generally speaking its use is restricted and indirect methods are much more powerful.

Most of the indirect methods of accelerating particles make use of high

making use of neutrons within a reacting pile; with these radioactive substances biological knowledge of great importance may be obtained. It is probable that the first benefits to arise from experiments on atomic energy will be in the form of a better understanding, first of animal, and then of human metabolism with corresponding benefits to all mankind.

(7) *Conclusion.*

He is rash who attempts to tell the future, especially in this novel field of atomic energy where there are no historical parallels to guide us. Naturally, there is some uncertainty in the accuracy of present-day estimates of the consequences to the world of the discovery of means for releasing atomic energy. If we realize the seriousness of the threat to our civilization that arises from the atomic bomb and take the steps which are needed to prevent war, we may in this way alone achieve benefits of the greatest value. If, in addition, it proves possible to use atomic energy for the supply of cheap power and especially if, as would then seem likely, coal mining becomes an occupation of diminishing importance, the discoveries in nuclear physics made during and after 1939 may give rise, in a few decades, to more material progress than has been achieved since man came to this earth. The discovery of atomic energy may be compared with the discovery of the steam engine; if this comparison is apt and if the development of atomic energy is carried out on an adequate scale, a new industrial revolution will follow quickly on the heels of these discoveries. The future is full of hope and promise, but only if we see to it that never again are these new powers used for killing and destruction.

*REFERENCES*

[1] *One World or None*, McGraw-Hill (1946), p. 21.
[2] Smyth Report, 12.33.

frequency alternating potentials. If arrangements are made whereby the particles being accelerated pass many times through the applied voltage, it is possible to impart to them an energy of say 10 MeV when the accelerating potential is only 200 kV. The simplest arrangement employing this principle is the linear accelerator. A diagram showing the principle of this device is given in Fig. 43. Within an evacuated tube are a number of cylindrical electrodes which have lengths depending upon their positions in the tube.

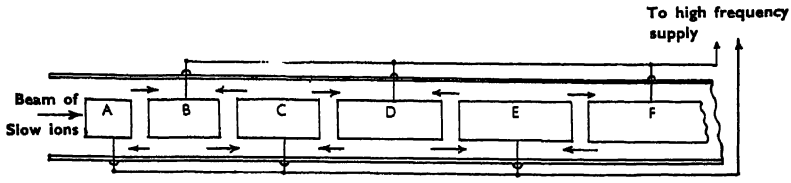



**Fig. 43.** The arrangement of the electrodes in a linear accelerator.

Alternate cylinders are connected together and between the two sets so formed a high frequency electric potential is applied. A beam of positive ions moves down the tube. Let us fix our attention on those ions which cross from cylinder A to cylinder B at a moment when the electric fields are momentarily maximum and directed as shown by the arrows drawn above the electrodes. These ions will be accelerated and their speed when within B will be greater than it was when they were within A. During the time the particles are moving inside B, the field falls and reverses, and if cylinder B is of the correct length these ions will cross from B to C when the electric fields are as indicated by the arrows below the electrodes; the particles, now between B and C, are again accelerated. Clearly, the ions are accelerated at both gaps because it takes them one half cycle of the high frequency potential to pass from one gap to the next. This can take place as many times as is desired, and provided that the length of each cylinder is such that the accelerated ions take one half cycle to pass from one gap to the next the ions are accelerated each time they cross a gap. Practical limitations are quite serious; the apparatus is very long and in consequence there is a difficulty in preventing ions from drifting sideways and being caught on the electrodes. This method has been successfully employed, but it is described here not because of its importance but because it provides a useful introduction to a description of the cyclotron.

In the cyclotron the ion paths are made circular because of the presence of a strong magnetic field. This addition causes some considerable simplifications for then there are required only two accelerating electrodes which the

ions traverse very many times. Ions must traverse the gaps between the electrodes at the appropriate instants, and this is achieved by using the correct value for the magnetic field.

The behaviour of ions in a magnetic field is so simple that it is worth deriving the formulæ on which the principle of the cyclotron depends. When ions of mass m carrying the electronic charge e move with velocity v in a magnetic field of strength B they experience a force Bev. This force is at right angles both to the magnetic field and to the direction of motion of the particle; consequently the speed of the particle is unaltered but its direction of motion is continually changing and it describes a circle such that the centrifugal force balances the force arising from the magnetic field.

$$\text{Hence } Bev = \frac{mv^2}{r}, \quad \text{or} \quad Ber = mv.$$

We use this relation to determine firs the time taken for the ion to complete one circle in the magnetic field. In doing so it travels a distance $2\pi r$ at a velocity v; this takes a time $\frac{2\pi r}{v}$, i.e., $\frac{2\pi m}{Be}$.

This time does not depend on the velocity of the ion and as long as m and B remain constant the particle describes a complete circle in the field in a time which is independent of its speed.

We do need another relation: that between the energy of the particle and the radius of its orbit. If V is the energy of the ion in electron volts we know that $Ve = \frac{1}{2}mv^2$, or $v = \sqrt{\frac{2Ve}{m}}$.

Hence $Ber = \sqrt{2Vem}$, i.e., $r = \frac{1}{B}\sqrt{\frac{2Vm}{e}}$ or $V = \frac{B^2r^2e}{2m}$.

For deuterons $\left(\frac{e}{m} = 5 \times 10^7 \text{ coulombs per kg.}\right)$ when $B = 1.4$ weber per sq. m (14 000 gauss) and $r = 1$ metre we find that $V = 5 \times 10^7$ electron volts. For reasons which will be given below the cyclotron is not able to give quite this much energy to deuterons.

The following is a description of the cyclotron. A metal box, which can be evacuated, is placed between the poles of a large electromagnet. Within the box are two hollow electrodes. These electrodes and their position in the magnetic field are shown in Fig. 44 and in a plan of the arrangement shown in Fig. 45. Here it is seen that the hollow electrodes are D-shaped; they are known as the D's. Between the D's, and at their common centre, is a device for producing an intense electron stream through which a slow current of

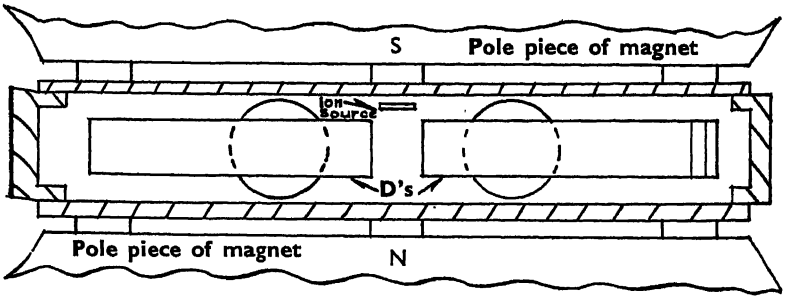



**Fig. 44.** A section showing the disposition of apparatus between the poles of a cyclotron magnet.

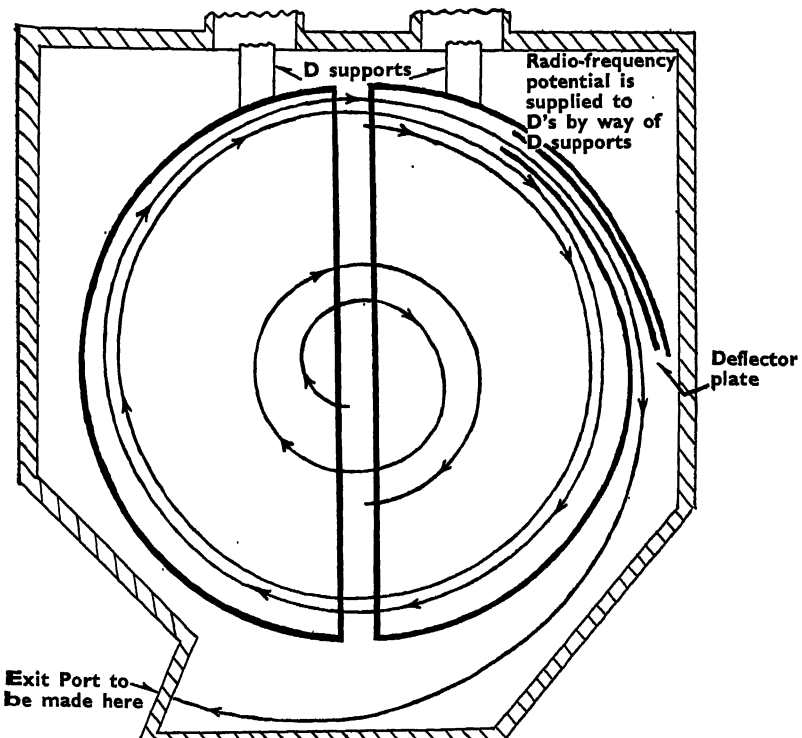



**Fig. 45.** A plan of cyclotron electrodes showing the ion paths.

gas is led into the highly evacuated box. This arrangement forms an ion source very similar to that used in the electromagnetic separation method as discussed in Chapter 14. It provides a copious supply of positive ions near the centre of the D system. Now between the D's a large radio-frequency voltage is applied which causes many ions to be drawn into one or other of the D's; in the presence of the magnetic field the ions describe circles. As long as an ion is within a D it is uninfluenced by any change of potential of the D, but eventually it will leave one D and travel across the gap towards the other one. If the frequency of the applied voltage is correct, the potential between the D's will be such as to accelerate the ion and in consequence on entering the other D it will have a higher velocity, and within this D it will describe a semicircle of larger diameter than the previous one. The greater circumference of this circle compensates for the greater velocity of the particle —our formula shows that the time of description of a circle does not depend on the velocity—and when the electric potential has reversed again the ion is passing from one D to the other and is being accelerated. As long as the ion keeps in step with the high frequency field it will continue to gain energy each time it crosses from one D to the other. This will happen if the magnetic field is constant and if the energy of the ion does not become great enough to bring about an appreciable increase of its mass. In practice, when the particle has been given an energy of between perhaps 10 and 20 MeV its mass has increased so much that it can no longer keep in step with the changes in the electric field. It might be thought that the disadvantages of this increase of mass could be overcome by using a magnetic field which is strongest near the edge where the mass of the ion is greatest, but this is not practicable. The cyclotron is able to produce large numbers of high energy particles because ions do not drift to the D's; it is for this reason that ions are able to describe perhaps 100 circles and that some ions can pass 200 times through the maximum potential between the D's. And this is only possible when the magnetic field is stronger at the centre than in the regions near the outside where high energy particles move. Thus although the cyclotron will give particles of very high energy, there is a limit imposed by the increase of mass predicted by the theory of relativity.

It remains to mention the means used for deflecting the high speed ions from their circular paths within the D's. This is done by providing in one D a curved metal plate connected to a source of high steady negative potential. When ions describe a circle large enough to bring them near this deflector plate, they are forced out of their normal paths and pass through an opening in the D. Thereafter they may take a path which causes them to fall upon a target that is to be bombarded, or they may be used in any other manner desired.

The ion beams obtainable from a cyclotron carry a current of the order of $10^{-5}$ amp., corresponding to $6 \times 10^{13}$ ions per second. Thus even these small currents of high energy ions provide fast particles in very much greater number and of higher energy than those available from any radioactive source.

Detailed information concerning cyclotrons is given in "Cyclotrons", W. B. Mann, (Methuen).

## APPENDIX II

# TRACER CHEMISTRY

In the study and applications of radioactivity special chemical methods are often employed with great advantage. Let us consider, as a case in point, the separation of radium from uranium and its products. The radium content of geologically old uranium ores is rather less than one part of radium to a million of uranium, so that if the uranium and radium are brought into solution, there will be a large amount of solution for a very small amount of dissolved radium. In these circumstances, attempts to precipitate the radium as insoluble sulphate may be unsuccessful, for the minute amount of radium may remain in solution in the very much larger amount of water. This precipitation can be achieved if a soluble salt of barium is present in the solution or is added to it. The precipitate of insoluble sulphates contains barium mixed with radium; after the removal of other impurities, the radium and barium are converted into chlorides; in order to obtain the radium which was originally mixed with the uranium, it is only necessary to work up the chlorides to separate the radium from barium.

This procedure is frequently advantageous. Another case, which shows the process in a slightly different form, arises when artificial radio-phosphorus is made by bombarding aluminium with $\alpha$ particles. This form of phosphorus, which emits positrons, was one of the artificial radioactive substances discovered in the pioneer work of the Joliots. They showed that bombarded aluminium was radioactive and emitted positrons. On bringing the aluminium into solution, adding a soluble phosphorus compound and precipitating the phosphorus, it was found that the positron activity was in the precipitate and not in the solution. This observation, together with experiments which showed that the radioactivity did not precipitate with aluminium or magnesium, for example, served to show the chemical nature of the radioactive substance, despite the fact that the total amount available was far less than $10^{-12}$g. Some other cases in which this process has been invaluable have been mentioned in various parts of this book. Here it is sufficient to recall the use of tracer chemistry in the first investigations of the chemical properties of plutonium and—with less satisfactory results—in the investigations of the nature of what were believed to be trans-uranic elements but were really fission fragments and the products of their radioactive decay.

Further information on this subject will be found in "Radioactivity", Hevesy and Paneth, (Oxford University Press), CHAP. XVII.

## APPENDIX III

# PROBABILITY IN RADIOACTIVITY

In the realm of dynamics, the motion of a body is described in terms of the motion of the particles of which it is made. It was at one time felt that if it were possible to specify the position and velocity of every particle in a body and in any other bodies with which it came in contact, the complete motion of the body would be determined and its position at any given moment could be predicted. It has not been possible to use any such idea so that it gives results which agree with observations of radioactivity in particular and of nuclear processes in general.

The simplest type of process to discuss is the radioactive decay of a substance like radium. Considered in bulk, radium has a half life of about 1600 years; that is 1 g. of radium to-day will 1600 years hence be emitting $\alpha$ particles and $\gamma$ rays at a rate which shows that only 0.5 g. of radium remains. This remaining half gram will exhibit the same behaviour, and in the next period of 1600 years half of it will go through a radioactive transformation and the other half will remain. The regularity and predictability of this radioactive decay is in marked contrast to what is observed when a more detailed view is taken. In a sample of radium containing $7 \times 10^{10}$ radium atoms, 1 radium atom, on the average, decays every second. Hence in a day nearly $10^5$ atoms of radium have emitted $\alpha$ particles and have changed their chemical nature. What is it that makes these atoms decay now when nearly $2 \times 10^{10}$ atoms within the sample will live for a further period of over 3200 years? To this question no answer has been found; perhaps there is no answer. The observation of the behaviour of radium, however, makes it necessary to direct attention to average behaviour, rather than to the behaviour of individual atoms. For although it is true that amongst $7 \times 10^{10}$ radium atoms there is, on the average, one atom decaying every second, there will be occasions when a period of 3 or 4 seconds will elapse without the transformation of a single radium atom. Observations extending over limited periods may therefore give quite a wrong impression of the rate of radioactive decay of a given substance, but as the period of observation is extended so that the number of atoms observed to decay is increased, the value of the average number of atoms decaying per second becomes known with more and more reliability, although even extended measurements will be subject to uncertainty arising from the fluctuating process of radioactive decay.

The whole process is described mathematically by supposing that radioactive decay follows the laws of chance. There is a certain definite chance that any given atom of radium, now in existence, will decay within the next second; each atom behaves in a manner which is uninfluenced by what other atoms are doing. This chance of decay of an atom in 1 second is $\lambda$, the transformation constant of the radioactive substance. In the case of radium $\lambda$ is $1.373 \times 10^{-11}$ per sec. so that in a sample of radium containing about $7 \times 10^{10}$ atoms, on the average 1 atom decays every second. This theory does not attempt to explain why a radioactive atom decays, for it is only a quantitative description; as such it is in complete accord with what is observed.

In no problem of nuclear physics is it possible to predict the behaviour of a single nucleus. But by discussing the matter in terms of probabilities it is possible to form a precise picture of what will happen, on the average, if the experiment is repeated a sufficient number of times. This idea is implicit in many numerical values given throughout this book; neutron collision and neutron capture cross sections, fission cross sections and the number of neutrons released per fission, reproduction factors of a pile or of a bomb and the life time of a neutron generation, all are statistical averages, and on occasion cases will occur in which there are most marked departures from these averages. Without the use of this idea, no interpretation of the results of nuclear physics experiments can make sense.

## ENERGY UNITS

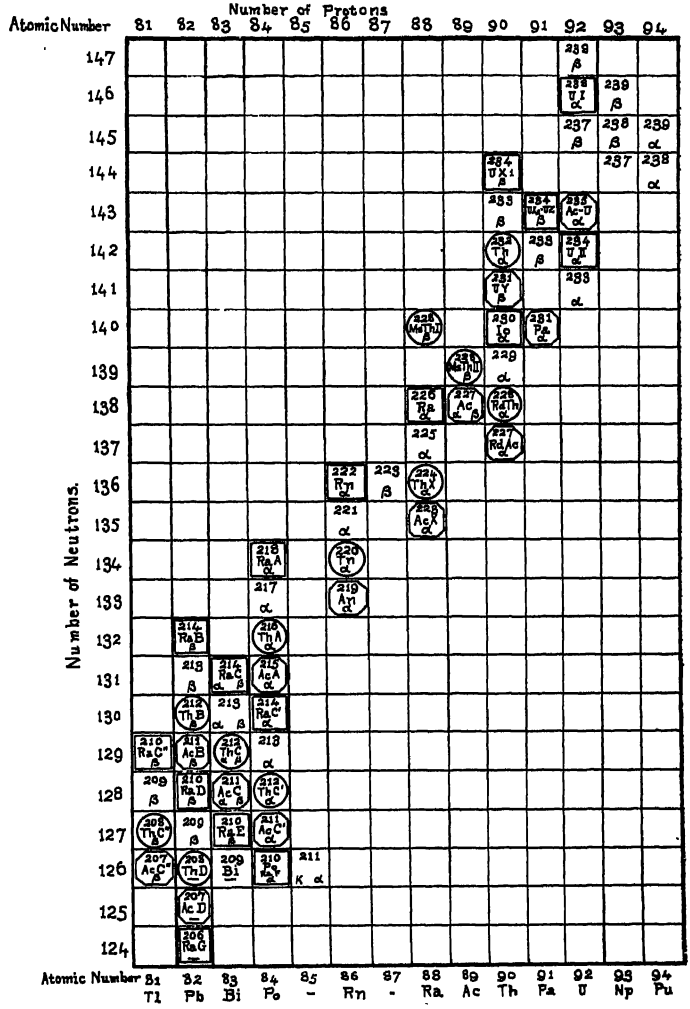
1 eV = $1.6 \times 10^{-19}$ joules or $1.6 \times 10^{-12}$ ergs.

1 mass unit = $1.49 \times 10^{-10}$ joules or $1.49 \times 10^{-3}$ ergs.

1 MeV per molecule of 1 g. molecule
= $9.65 \times 10^{10}$ joules
= $2.7 \times 10^{4}$ kWh
= $2.3 \times 10^{10}$ g. cal.

0.001 Mass unit per molecule of 1 g. molecule
= $9.0 \times 10^{10}$ joules
= $2.5 \times 10^{4}$ kWh
= $2.1 \times 10^{10}$ g. cal.

# THE HEAVY RADIOACTIVE SUBSTANCES



Substances in the uranium-radium series are enclosed in squares, those in the thorium series in circles and those in the actinium series in octagons. Radioactive substances discovered since 1939 are not shown as belonging to any of these series, although some of them are part of the uranium and actinium series. Others of the substances listed do not belong to any of the old radioactive series. It is likely that this diagram omits some heavy radioactive substances which have been investigated during the recent war.

It is to be noted that the emission of a $\beta$ particle transforms a substance to an element having one less neutron and one more proton than the parent; the emission of an $\alpha$ particle removes two protons and two neutrons. The relative positions of parent and product are seen by considering, as an example, the case of $U^{239}$ which becomes $Np^{239}$ after one $\beta$ ray emission; a second $\beta$ ray emission transforms $Np^{239}$ to $Pu^{239}$ and then an $\alpha$ ray emission converts $Pu^{239}$ to $U^{235}$.

## A TABLE OF ELEMENTS*

The mass numbers of radioactive isotopes are written in italics.

| *Element* | *Known Isotopes* | | | | | | | | | *Symbol* | *Atomic No* |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Hydrogen | 1 | 2 | *3* | | | | | | | H | 1 |
| Helium | 3 | 4 | *6* | | | | | | | He | 2 |
| Lithium | 6 | 7 | *8* | | | | | | | Li | 3 |
| Beryllium | *7* | 9 | 10 | | | | | | | Be | 4 |
| Boron | 10 | 11 | *12* | | | | | | | B | 5 |
| Carbon | *10* | *11* | 12 | 13 | *14* | | | | | C | 6 |
| Nitrogen | *13* | 14 | 15 | *16* | | | | | | N | 7 |
| Oxygen | *15* | 16 | 17 | 18 | *19* | | | | | O | 8 |
| Fluorine | *17* | *18* | 19 | *20* | | | | | | F | 9 |
| Neon | *19* | 20 | 21 | 22 | *23* | | | | | Ne | 10 |
| Sodium | *22* | 23 | *24* | | | | | | | Na | 11 |
| Magnesium | *23* | 24 | 25 | 26 | *27* | | | | | Mg | 12 |
| Aluminium | *26* | 27 | *28* | *29* | | | | | | Al | 13 |
| Silicon | *27* | 28 | 29 | 30 | *31* | | | | | Si | 14 |
| Phosphorus | *29* | *30* | 31 | *32* | | | | | | P | 15 |
| Sulphur | *31* | 32 | 33 | 34 | *35* | 36 | | | | S | 16 |
| Chlorine | *33* | *34* | 35 | *36* | 37 | *38* | | | | Cl | 17 |
| Argon | *35* | 36 | *37* | 38 | 40 | *41* | | | | A | 18 |
| Potassium | *38* | 39 | *40* | 41 | *42* | | | | | K | 19 |
| Calcium | 40 | 42 | 43 | 44 | *45* | 46 | 48 | *49* | | Ca | 20 |
| Scandium | *41* | *43* | *44* | 45 | *46* | *48* | *49* | | | Sc | 21 |
| Titanium | *45* | 46 | 47 | 48 | 49 | 50 | *51* | | | Ti | 22 |
| Vanadium | *48* | *50* | 51 | *52* | | | | | | V | 23 |
| Chromium | *49* | 50 | *51* | 52 | 53 | 54 | | | | Cr | 24 |
| Manganese | *51* | *52* | *54* | 55 | *56* | | | | | Mn | 25 |
| Iron | *53* | 54 | *55* | 56 | 57 | 58 | *59* | | | Fe | 26 |
| Cobalt | *55* | *56* | *57* | *58* | 59 | *60* | | | | Co | 27 |
| Nickel | *57* | 58 | 60 | 61 | 62 | *63* | 64 | | | Ni | 28 |
| Copper | *62* | 63 | *64* | 65 | *66* | | | | | Cu | 29 |
| Zinc | *63* | 64 | *65* | 66 | 67 | *68* | *69* | 70 | | Zn | 30 |
| Gallium | *65* | *66* | *67* | *68* | 69 | *70* | 71 | *72* | | Ga | 31 |
| Germanium | 70 | *71* | 72 | 73 | 74 | *75* | 76 | *77* | | Ge | 32 |
| Arsenic | *74* | 75 | *76* | *78* | | | | | | As | 33 |
| Selenium | 74 | *75* | 76 | 77 | 78 | 80 | 82 | *83* | | Se | 34 |
| Bromine | *78* | 79 | *80* | 81 | *82* | *83* | *84* | *85* | | Br | 35 |
| Krypton | 78 | 80 | 82 | 83 | 84 | *85* | 86 | *88* | *89* | Kr | 36 |
| Rubidium | 85 | *86* | *87* | *88* | *89* | | | | | Rb | 37 |
| Strontium | 84 | *85* | 86 | 87 | 88 | *89* | | | | Sr | 38 |
| Yttrium | *87* | *88* | 89 | *90* | | | | | | Y | 39 |

* The existence of all the types of nuclei listed here is believed to be certain. There are others of doubtful existence and probably still further types which have yet to be discovered.

| *Element* | *Known Isotopes* | *Symbol* | *Atomic No.* |
|---|---|---|---|
| Zirconium | *89* 90 91 92 · 94 96 | Zr | 40 |
| Niobium | *92* 93 *94* | Nb | 41 |
| Molybdenum | 92 94 95 96 97 98 100 | Mo | 42 |
| Masurium | ? | Ma | 43 |
| Ruthenium | 96 98 99 100 101 102 *103* 104 | Ru | 44 |
| Rhodium | 103 *104* *105* | Rh | 45 |
| Palladium | 102 104 105 106 108 110 *111* *112* | Pd | 46 |
| Silver | *106* 107 *108* 109 *110* *111* *112* | Ag | 47 |
| Cadmium | 106 108 110 111 112 113 114 *115* 116 *117* | Cd | 48 |
| Indium | 113 *114* 115 *116* *117* | In | 49 |
| Tin | 112 *113* 114 115 116 117 118 119 120 122 124 | Sn | 50 |
| Antimony | *120* 121 *122* 123 *124* *127* *129* | Sb | 51 |
| Tellurium | 120 *121* 122 123 124 125 126 *127* 128 *129* 130 *131* *135* | Te | 52 |
| Iodine | *124* *126* 127 *128* *130* *131* *133* *135* | I | 53 |
| Xenon | 124 126 128 129 130 131 132 134 *135* 136 *139* *140* *141* | Xe | 54 |
| Caesium | 133 *134* *136* *139* *141* | Cs | 55 |
| Barium | 130 132 133 134 135 136 137 138 *139* *140* *141* | Ba | 56 |
| Lanthanum | 139 *140* *141* | La | 57 |
| Cerium | 136 138 140 *141* 142 | Ce | 58 |
| Praseodymium | *140* 141 *142* | Pr | 59 |
| Neodymium | *141* 142 143 144 145 146 148 150 | Nd | 60 |
| Illinium | ? | Il | 61 |
| Samarium | 144 147 148 149 150 152 154 | Sm | 62 |
| Europium | 151 153 | Eu | 63 |
| Gadolinium | 152 154 155 156 157 158 160 | Gd | 64 |
| Terbium | 159 *160* | Tb | 65 |
| Dysprosium | 158 160 161 162 163 164 *165* | Dy | 66 |
| Holmium | 165 | Ho | 67 |
| Erbium | 162 164 166 167 168 170 | Er | 68 |
| Thulium | 169 | Tm | 69 |
| Ytterbium | 168 170 171 172 173 174 176 | Yb | 70 |
| Lutecium | 175 *176* | Lu | 71 |
| Hafnium | 174 176 177 178 179 180 *181* | Hf | 72 |
| Tantalum | *180* 181 *182* | Ta | 73 |
| Tungsten | 180 182 183 184 186 | W | 74 |
| Rhenium | 185 187 | Re | 75 |
| Osmium | 184 186 *187* 188 189 190 192 | Os | 76 |
| Iridium | 191 193 | Ir | 77 |
| Platinum | 192 194 195 196 198 *199* | Pt | 78 |
| Gold | 197 *198* *199* | Au | 79 |
| Mercury | 196 *197* 198 199 200 201 202 204 *205* | Hg | 80 |
| Thallium | 203 205 *207* *208* *209* *210* | Tl | 81 |
| Lead | 204 206 207 208 *209* *210* *211* *212* *213* *214* | Pb | 82 |
| Bismuth | *207* 209 *210* *211* *212* *213* *214* | Bi | 83 |
| Polonium | *210* *211* *212* *213* *214* *215* *216* *217* *218* | Po | 84 |
| — | *211* | — | 85 |
| Radon | *219* *220* *221* *222* | Rn | 86 |
| — | *223* | — | 87 |
| Radium | *223* *224* *225* *226* *228* | Ra | 88 |

| *Element* | *Known Isotopes* | *Atomic Symbol* | *No.* |
|---|---|---|---|
| Actinium | *227 228* | Ac | 89 |
| Thorium | *227 228 229 230 231 232 233 234* | Th | 90 |
| Protoactinium | *231 233 234* | Pa | 91 |
| Uranium | *233 234 235 237 238 239* | U | 92 |
| Neptunium | *237 238 239* | Np | 93 |
| Plutonium | *238 239* | Pu | 94 |

## THE PERIODIC TABLE

The numbers below the chemical symbols are atomic numbers.

| *Period* | I | II | III | IV | V | VI | VII | 0 | VIII |
|---|---|---|---|---|---|---|---|---|---|
| I | H 1 | | | | | | | He 2 | |
| II | Li 3 | Be 4 | B 5 | C 6 | N 7 | O 8 | F 9 | Ne 10 | |
| III | Na 11 | Mg 12 | Al 13 | Si 14 | P 15 | S 16 | Cl 17 | A 18 | |
| IV | K 19 | Ca 20 | Sc 21 | Ti 22 | V 23 | Cr 24 | Mn 25 | | Fe 26 Co 27 Ni 28 |
| | Cu 29 | Zn 30 | Ga 31 | Ge 32 | As 33 | Se 34 | Br 35 | Kr 36 | |
| V | Rb 37 | Sr 38 | Y 39 | Zr 40 | Nb 41 | Mo 42 | Ma 43 | | Ru 44 Rh 45 Pd 46 |
| | Ag 47 | Cd 48 | In 49 | Sn 50 | Sb 51 | Te 52 | I 53 | Xe 54 | |
| VI | Cs 55 | Ba 56 | R.E. 57-71 | Hf 72 | Ta 73 | W 74 | Re 75 | | Os 76 Ir 77 Pt 78 |
| | Au 79 | Hg 80 | Tl 81 | Pb 82 | Bi 83 | Po 84 | — 85 | Rn 86 | |
| VII | — 87 | Ra 88 | Ac 89 | Th 90 | Pa 91 | U 92 | | | |

| Rare Earths: | La 57 | Ce 58 | Pr 59 | Nd 60 | Il 61 | Sm 62 | Eu 63 | Gd 64 | Tb 65 | Dy 66 | Ho 67 | Er 68 | Tm 69 | Yb 70 | Lu 71 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|

If a new group of rare earths begins at uranium, the space in the periodic table occupied by uranium should also contain $^{Np}_{93}$ and $^{Pu.}_{94}$

## PARTICLES AND RAYS

| *Particle* | *Symbol* | *General Description* | *Charge* | *Mass when at rest* |
|---|---|---|---|---|
| Proton | p or $H_1^1$ | Fundamental positively charged heavy particle : nucleus of the hydrogen atom. | +1 | 1.00758* |
| Neutron | n or $n_0^1$ | Fundamental heavy particle of zero charge. Believed to transform into a proton and an electron. | 0 | 1.00893 |
| Electron | $\beta$ or e- | Fundamental negative unit of charge. Emitted by many natural and artificial radioactive substances : then called a $\beta$ particle. | —1 | 0.00055 |
| Positron | e+ | Positive electron. Emitted by certain artificial radioactive substances. Formed when $\gamma$ rays pass through heavy metals. | +1 | 0.00055 |
| Deuteron | $H_1^2$ or $D_1^2$ | Heavy hydrogen nucleus : may be converted by $\gamma$ rays into a proton and a neutron. | +1 | 2.01418* |
| $\alpha$ particle | $\alpha$ or $He_2^4$ | Nucleus of the helium atom. Close combination of two protons and two neutrons. Emitted spontaneously by some natural radioactive substances. | +2 | 4.0028* |
| $\gamma$ rays | $\gamma$ or $h\nu$ | Electromagnetic radiation emitted by atomic nuclei. Moves with the velocity of light. | 0 | — |

1 Mass unit $= 1.66 \times 10^{-24}$ g.
Unit charge $= 1.6 \times 10^{-19}$ coulombs

*The mass listed is a nuclear mass. Atomic masses are obtained from those given by adding 1 electronic mass in the case of hydrogen and 2 in the case of helium

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